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RESEARCH MEMORANDUM

EFFECT OF BURNER DESIGN VARIABLES ON PERFORMANCE OF

16-INCH-DIAMETER RAM-JET COMBUSTOR USING

GASEOUS-HYDROGEN FUEL

By H. George Krull and Richard R. Burley

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

EFFECT OF BURNER DESIGN VARIABLES ON PERFORMANCE OF 16-INCH-DIAMETER RAM-JET COMBUSTOR USING GASEOUS-HYDROGEN FUEL

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SUMMARY

An evaluation of the effect of geometric design variables on the performance of a 16-inch-diameter ram-jet combustor using gaseous hydrogen as a fuel was obtained over a range of combustor total pressures from 7 to 44 inches of mercury absolute. Equivalence ratio was varied from 0.1 to 1.0 at a combustor inlet temperature of 1100° R.

Peak combustion efficiencies ranging from 81 to 98 percent were obtained with a burner 18 inches long (measured from fuel injectors to exhaust-nozzle outlet) over a range of burner total pressures from 10 to 35 inches of mercury absolute. Combustion efficiency was generally insensitive to pressure down to 20 inches of mercury absolute but decreased rapidly at lower pressures, particularly for the short burner lengths.

In general, there was very little gain in combustion efficiency by increasing the combustor length beyond 30 inches. Combustion was stable over a wide range of equivalence ratios. No rich blowout was encountered. Lean blowout was encountered only at very low burner total pressures and low equivalence ratios. Combustion screech was encountered and completely eliminated with a perforated acoustical liner.

INTRODUCTION

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The analytical study of reference 1 indicates the possibility of extending aircraft performance by using hydrogen as a fuel. Hydrogen can extend aircraft ranges because of its high heating value, which is about 2.75 times the heating value of the average hydrocarbon fuel (JP-4). The density of liquid hydrogen is low (about one-tenth that of hydrocarbon fuel), so relatively large fuel tanks are needed. The wings and fuselage of an airplane designed for high altitude are much greater than those of an airplane designed for a low altitude with the same cruise speed. The

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high heating value of the low density hydrogen can be utilized by air-
planes designed for high altitude because of the large volume available
for fuel tankage. Therefore, hydrogen is particularly attractive for
high-altitude flight which means the combustors will have to operate at
low pressures. In addition, low engine weight is of primary importance
at high altitude, so the combustor must also be as short as possible.
Experimental investigations were therefore needed to determine whether
or not short burners could be designed to operate efficiently at low
pressures and to determine burner design principles.

As a first approach to the problem, the effect of combustor length
on burner performance was studied using a 16-inch-diameter ram-jet com-
bustor. This preliminary investigation showed that hydrogen provided
high combustion efficiency over a wide range of equivalence ratios (ref.
2). The data, however, covered only relatively high burner pressures
(approximately 13 to 50 in. Hg abs) because of a facility limit. Addi-
tional experimentation was therefore required to obtain data at the low-
burner pressures.

The present investigation determined the effect of burner design
variables on the performance of a 16-inch-diameter ram-jet combustor
over a range of burner-inlet total pressures from 7 to 44 inches of mer-
cury absolute and established some desirable burner design principles
for this fuel.

Data were obtained over the following range of burner variables:
equivalence ratio, 0.1 to 1.0; inlet temperature, 1100° R; burner length,
18, 26, and 44 inches; and exhaust-nozzles of 0.4 and 0.5
(nozzle exit area/max. area of combustor). The effect of injector shape,
injection direction, and screech tendency was studied over the range of
burner variables.

APPARATUS AND INSTRUMENTATION

Test Facility

The test facility for this investigation was basically a free-jet
type that included a supersonic nozzle and a second throat. The second
throat was blocked off and the ram-jet combustor was therefore operated
as a direct-connect installation for these tests as shown schematically
in figure 1. Air entered the facility through a combustion-type pre-
heater and a surge tank and was ducted subsonically to the combustor-
entrance duct.

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Combustor

The 16-inch-diameter ram-jet combustor used in this investigation is shown schematically in figure 2. The long entrance duct ahead of the combustor was used to simulate supercritical operation. This was done by choking the flow at the throat of the entrance duct and then expanding it supersonically over a portion of the divergent section of the entrance duct. The combustion chamber had an inside diameter of 16 inches and was water jacketed. The combustion-chamber length was varied from 18 to 44 inches by inserting various spool pieces. The combustion-chamber length was defined as the distance from the plane at the centerline of the downstream fuel injectors to the plane of the exhaust-nozzle exit. The fuel injectors were located in an annulus between the combustion-chamber outer wall and the centerbody. The outer-wall section which contained the injectors was so arranged that the injectors could be either located in one plane or staggered. Two convergent exhaust nozzles were used with throat areas equal to 40 and 50 percent of the combustion-chamber (16-in. diameter) cross-sectional area. The combustor was ignited by two spark plugs whose electrodes sparked against the sides of the fuel injectors as shown in figure 3.

Burner Components and Test Configurations

Fuel injectors. - Two types of fuel injector system were used as shown in figure 4. The concentric-ring fuel-injector system, which was the same as configuration A of reference 2, consisted of three concentric rings with six supply struts. These rings were split into six equal sectors, one of which is shown in figure 5(a). This injector is referred to as injector 1. In the complete system there were a total of 432 fuel orifices each with a diameter of 0.055 inch. Nine-tenths of the fuel was sprayed normal to the gas stream while the remainder was sprayed downstream. The projected blocked area of this configuration was about 20 percent.

The second type of fuel-injector system consisted of 38 alternately long and short radial injectors equally spaced circumferentially (fig. 4(b)). The long and short injectors extended 5 and $2\frac{1}{2}$ inches, respectively, into the burner. For some configurations the injectors were staggered so that the short injectors were $1\frac{3}{8}$ inches upstream of the long injectors. Three different radial fuel-injector shapes were investigated. These injectors had V-, kidney-, and round-shaped cross-sectional areas, as shown in figure 5(b), which were referred to as injectors 2a, 2b, and 2c, respectively. All injectors had a width of 1/2 inch.

The round injectors were investigated with four injection directions, downstream, upstream, normal, and downstream at 45° to airflow direction (assuming axial flow). Cross-sectional sketches of these injectors (2c to 2f) are shown in figure 5(b). The radial locations of the injection points were the same for injectors 2a to 2f. Injectors 2a to 2d had single orifices at each injection point, which had a 0.0465-inch diameter, giving a total of 570 fuel orifices. Injectors 2e and 2f had double fuel orifices at each injection point that were 0.033 inch in diameter with a total of 1140 fuel orifices. Each set of injectors, however, had the same effective fuel-flow-orifice area.

For one configuration an acoustical liner was used which was spaced 1/2 inch from the outer wall. Use of the liner necessitated relocating the fuel orifices near the outer wall so that the liner would not burn out. This configuration had the same fuel injectors as injector 2f, except that the outer two sets of fuel orifices were relocated as shown by injector 3.

The projected blocked area of each of the radial fuel-injector configurations was 45 percent.

Acoustical liner. - A perforated acoustical liner was installed in one of the configurations investigated to eliminate combustion screech. A photograph of the liner is shown in figure 3. The liner extended 6 inches downstream and 2 inches upstream of the plane at the centerline of the long radial fuel injectors (the configuration with the liner had staggered fuel injectors), and it was spaced 1/2 inch from the outer wall. The liner was made of 1/16-inch-thick Inconel sheet with 3/16-inch perforations which were spaced on 1/2-inch centers.

Configurations. - The fuel injectors, burner lengths, and exhaust nozzles used in each of the configurations investigated are shown in the following table:

Configuration	Fuel injectors	Burner length, in.			Screech liner	Exhaust nozzle	
		18	26	44		0.4	0.5
A	1 ($\oplus$)	X	X				X
B	2a ($\oslash$)	X					X
C	2b ($\oslash$)	X					X
D	2c ($\ominus$)	X					X
E	2d ($\bigcirc$)	X					X
F	2e ($\ominus$)	X					X
G	2f ($\oslash$)	X					X
H	a2f ($\bigcirc$ $\bigcirc$)	X					X
J	a3 ($\bigcirc$ $\bigcirc$)	X	X	X	X	X	X

a Fuel injectors staggered.

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Instrumentation

The stations at which the temperature and pressure instrumentation were located are shown in figure 2. Total temperature and pressure were measured just upstream of the bellmouth inlet at station 1. Wall static pressures were measured just upstream of the fuel injectors at station 2. These wall static measurements were used to calculate burner-inlet conditions. A water-cooled rake was used to obtain a total-pressure survey at the exhaust-nozzle exit (station 3). This pressure survey was used to calculate combustion efficiency and combustor-inlet airflow. Static pressure was measured just downstream of the exhaust-nozzle exit so that it could be determined whether or not the nozzle was choked. The combustor fuel flow was measured with an A.S.M.E. flat-plate orifice. A telescope installed in the rear of the test chamber afforded visual observation of the combustion chamber through the exhaust nozzle.

PROCEDURE

The combustor-inlet air temperature was raised to 1100° R by the combustion preheater. The combustor-inlet total pressure or airflow was set at the desired value by a valve downstream of the preheater. The exhaust nozzle was always choked except during ignition of those configurations which were hard to start at low pressures or airflows. For these configurations the burner was ignited at the low airflows by partially closing the exhaust valve, which unchoked the exhaust nozzle and increased the burner pressure. Data were obtained over a range of equivalence ratios from 0.1 to 1.0 at constant airflow. The combustor airflow remained constant over the complete range of equivalence ratios because the entrance duct throat was always choked. Combustor unit airflow (w/A_b) was varied from approximately 2.75 to 11.4 pounds per second per square foot and combustor-inlet total pressure varied from 7 to 44 inches of mercury absolute.

The symbols and methods of calculation used in this report are presented in appendixes A and B, respectively.

RESULTS AND DISCUSSION

In a previous unreported investigation it was shown that when using hydrogen as a fuel, the conventional method of injecting the fuel upstream of a flameholder could not be used. When upstream fuel injection was tried, flashback occurred and the flame seated on the fuel injectors. Therefore, for all the configurations presented herein the fuel injectors also served as flameholders.

The performance of configuration A of reference 2 was obtained over
a range of combustor-inlet total pressures from 8 to 44 inches of mer-
cury absolute. These data are shown in figure 6. Combustion efficiency,
burner-inlet total pressure, and percent burner total-pressure loss are
plotted against equivalence ratio for combustor lengths of 26 and 18
inches. The data obtained at high pressures with the 26-inch combustor
agreed very well with the data of reference 2 obtained in a different
facility (fig. 6(a)). The peak combustion efficiency decreased from 94
to 77 percent as the combustor-inlet total pressure decreased from 29
to 10 inches of mercury with an attendant decrease in unit airflow from
7.96 to 2.75. The data did not extend to an equivalence ratio of 1.0
at the high unit airflows because of a fuel-flow limit. At the lower
unit airflows, the combustion efficiency decreased more rapidly to either
side of the peak than at the higher unit airflows.

When the burner was shortened to 18 inches, much lower performance
was obtained as shown in figure 6(b). The peak combustion efficiency
dropped 5 percentage points below that of the 26-inch burner at the high
unit airflow, while at the lowest unit airflow the peak efficiency drop-
ped 27 percentage points. At the lowest unit airflow, combustion was
very unstable. Lean blowout occurred at an equivalence ratio of 0.77 as
compared with 0.3 with the 26-inch burner. The burner total-pressure
loss varied from 2 to 6 percent with both the 18- and 26-inch burners
(injector blockage, 20 percent).

Configuration A showed good performance at the high burner pres-
sures; however, at low pressures the performance was poor. This de-
crease in performance was probably due to poor fuel distribution (total
number of fuel orifices low) and low blockage.

Effect of Burner Design Variables on Burner Performance

The effect of various burner design variables on burner performance
was determined only at the critical operating conditions of low pressures
and 18-inch burner length, because there was little room for improvement
in burner performance at the high pressures and long lengths. The
length of the exhaust nozzle comprised two-thirds of the length of the
18-inch burner.

The configurations that follow had better fuel distribution (in-
creased number of fuel orifices) and higher blockage than configuration A
so that comparisons between these configurations and configuration A are
not valid.

Effect of injector shape. - The performance of the simple round ra-
dial injectors was as good as, or better than the performance of all the
injector shapes investigated. The effect of injector shape on perform-
ance is shown in figure 7. Three shapes were investigated, V, kidney,

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and round. Each shape had a 45-percent blockage and the same number of fuel orifices injecting downstream. Good combustion efficiency was obtained with all shapes over a wide range of equivalence ratios except at the lowest burner pressures or unit airflow, where lean blowout occurred between equivalence ratios of 0.6 and 0.8. The round injectors were used to study additional design variables because of their simple geometry.

Effect of injection direction. - The effect of fuel-injection direction on combustion efficiency is shown in figure 8. The four injection directions investigated with the round bar injectors were upstream, normal, downstream, and downstream 45° (45° to the axial direction). The radial locations of the injection points were the same for all configurations. The injectors spraying normal and downstream 45° had twice as many fuel orifices as the injectors spraying upstream and downstream. The effective fuel-flow area was the same for all four configurations. Combustion screech, shown in figure 8 by the dashed portion of the curves, was encountered with all injection directions except downstream injection. The start of audible screech is shown by the solid vertical line at the beginning of the dashed part of each curve. Upstream injection had the greatest tendency to screech (widest equivalence ratio range with screech). Screech was encountered at all pressures and started at equivalence ratios from 0.35 to 0.52. Normal injection showed the next greatest tendency toward screech, which started at the two highest pressures or unit airflows and at equivalence ratios of 0.45 and 0.54. Only mild screech was encountered with downstream 45° injection at the two highest unit airflows starting at equivalence ratios of 0.58 and 0.675. The stability limits of downstream 45° injection covered a wide range of equivalence ratios with lean blowout occurring at an equivalence ratio of 0.25.

In most previous investigations it was observed that when screech was encountered, the combustion efficiency remained high as the equivalence ratio was increased. There were, however, several cases during this investigation where combustor efficiency dropped sharply during screech as the equivalence ratio was increased. Since screech usually has an effect on combustion efficiency, the following discussion of the effect of injection direction on combustion efficiency only applies over the range of equivalence ratios where screech was not encountered.

The results show that for high combustion efficiency, "rich" burners require very good mixing of the fuel and air while "lean" burners require preservation of locally rich regions. Upstream and normal injection apparently did the best job of mixing the fuel and air since these configurations had the lowest combustion efficiency at the lean equivalence ratios and the highest peak combustion efficiencies at the rich equivalence ratios. Downstream injection was evidently the poorest mixer of fuel and air as shown by high combustion efficiency during lean operation and low combustion efficiencies during rich operation. A good compromise on performance over the full range of equivalence ratios was

obtained with downstream 45° injection, which provided generally inter-
mediate efficiency at both the rich and lean equivalence ratios.

Effect of staggering injectors. - Because downstream 45° injection
(configuration G) showed the best compromise performance over the com-
plete range of equivalence ratios and had only a slight tendency to
screech, it was chosen for further study. Since some source of energy
is required to maintain screech and a large amount of chemical energy is
released during combustion, it was thought that releasing the energy in
different planes by staggering the injectors would decrease the tendency
of the burner to screech. Therefore, the injectors were staggered by
moving the short injectors $1\frac{3}{8}$ inches upstream of the long injectors. The
effect of staggering the injectors is shown in figure 9. The over-all
burner performance was improved with this configuration and the screech
tendency decreased. There was only mild screech at the highest unit air-
flow for equivalence ratios of 0.7 and above. For staggered injectors
the combustion efficiency did not drop off at the high unit airflow when
screech occurred as it did when the injectors were not staggered.

Pressure-drop data showed that staggering had no perceptible effect
on the burner total-pressure loss.

Effect of screech liner. - Since screech is usually of a destruc-
tive nature, it was desirable to eliminate screech at all operating con-
ditions. In addition to staggering the injectors, an acoustical liner
was used in an attempt to eliminate screech completely. Liners spaced
1/4 and 3/8 inch from the outer wall of the burner were unsuccessful but
a liner 1/2 inch from the outer wall completely eliminated screech. All
the liners extended 6 inches downstream and 2 inches upstream of the sec-
ond tier of injectors. The use of a liner necessitated moving the outer
fuel orifices toward the center of the burner. The number of orifices
was not changed, because the orifices removed from the outer areas were
relocated between existing orifices (see fig. 5). The downstream end of
the liner was blocked off to force cooling air through the liner and into
the fuel-rich zone created by the relocated fuel orifices.

The effect of the liner on burner performance is shown in figure 10.
The liner caused no appreciable decrease in burner stability limits. Al-
though the over-all burner combustion efficiency dropped from 4 to 6 per-
cent because of the change in the fuel distribution, this drop might not
be as great with a larger diameter burner. Because a liner spaced 1/2
inch from the outer wall might stop screech in larger diameter burners,
this great a loss in combustion efficiency may not occur in larger diam-
eter burners where the fuel distribution would be better. The liner, is
durable as shown in (fig. 3). After 30 minutes of operation at an equiv-
alence ratio of 0.7, the liner showed no damage except slight warping.

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A comparison of the final configuration J with configuration A is shown in figure 11 where combustion efficiency is plotted against equivalence ratio for the 18-inch burner at the lowest pressure level (7 to 11 in. Hg abs) investigated. The stability limits and combustion efficiency were greatly increased with configuration J. The lean blowout limit was increased from an equivalence ratio of 0.77 to 0.26 and the peak combustion efficiency was increased from 52 to 78 percent. This performance improvement was attributed to the round fuel injectors, which sprayed fuel downstream 45°, the better fuel orifice distribution, the larger number of fuel orifices per unit cross-sectional area, and the increased blocked area of the injectors.

Blowout and starting limits. - Blowout limits were experienced only at lean equivalence ratios. These blowouts occurred only at the lowest pressure or unit airflow investigated and at various equivalence ratios depending upon the configuration (see figs. 6 to 10).

The round bars injecting fuel downstream showed the easiest tendency to start. With this configuration, the burner ignited at pressures as low as 6 inches of mercury absolute. The burner could be ignited at approximately 10 inches of mercury with the following injectors, which were located in the same plane: $\oplus$ (configuration A), $\oplus$, $\oplus$, $\oplus$, and $\oplus$. When using the round staggered injectors which sprayed downstream 45° to the airflow $\left(\oplus \atop \oplus\right)$, the burner started at pressures of 8 to 9 inches of mercury absolute. The hardest to start were the round injectors spraying upstream (11 to 14 in. Hg abs).

Performance Characteristics of Final Burner Configuration

Effect of burner-inlet Mach number. - The variation of burner-inlet Mach number with a 0.4 and 0.5 exhaust nozzle is shown in figure 12. The level of inlet Mach number varied 30 percent between the two nozzles. Since the Mach numbers were low, this variation had very little effect on combustion efficiency. This is shown by the general performance curves of the final configuration (configuration J) in figure 13. Combustion efficiency, burner-inlet total pressure, and percent burner total-pressure loss are plotted against equivalence ratio for burner lengths of 18, 26, and 44 inches and exhaust-nozzle sizes of 0.4 and 0.5. With the higher inlet Mach numbers, obtained with the 0.5 nozzle, the burner total-pressure loss was higher than with the lower inlet Mach numbers, obtained with the 0.4 nozzle (approximately 0.6 percentage points difference). No lean blowout was encountered with the low burner-inlet Mach numbers and the burner could be ignited at pressures as low as 6 inches of mercury absolute as compared with 8 or 9 inches of mercury absolute with the higher burner-inlet Mach numbers.

Effect of burner pressure and length. - The effect of burner total pressure and length on combustion efficiency is shown in figure 14 where combustion efficiency is plotted against burner length for constant values of burner-inlet total pressure and for given equivalence ratios. The burner lengths were 18, 26, and 44 inches and the nozzle sizes were 0.4 and 0.5.

The combustion efficiency for almost all conditions, including burner lengths of 18 inches and pressures as low as 10 inches of mercury absolute, was between 80 and 100 percent.

As expected there was a general trend of decreased combustion efficiency with decreasing pressure. Combustion efficiency was generally insensitive to pressure down to 20 inches of mercury absolute but decreased rapidly at lower pressures, particularly for the shorter lengths.

In general, there was little gain in combustion efficiency by increasing the combustor length beyond 30 inches.

SUMMARY OF RESULTS

The effect of burner design variables on the performance of a 16-inch-diameter ram-jet combustor using gaseous hydrogen as a fuel was studied over a range of burner total pressures from about 7 to 44 inches of mercury absolute at an inlet temperature of 1100° R. The configuration with the best performance had 38 radial fuel injectors. The injectors were staggered and injected fuel downstream at an angle of 45° to the axial direction. An acoustical liner was used to eliminate screech. The following results were obtained with this configuration:

Good performance was obtained at low burner pressures and short lengths. The shortest length investigated (18 in. from fuel injectors to exhaust-nozzle outlet) gave peak combustion efficiencies ranging from 81 to 98 percent over a pressure range from 10 to 35 inches of mercury absolute.

Combustion efficiency was generally insensitive to pressure down to 20 inches of mercury absolute but decreased rapidly at lower pressures, particularly for the short lengths.

In general, there was very little to be gained in combustion efficiency by increasing the combustor length beyond 30 inches.

The change in burner-inlet Mach number resulting from a variation in exhaust-nozzle size from 0.4 to 0.5 had very little effect on the combustion efficiency. This was probably because of the low level of the burner-inlet Mach numbers.

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With round radial bars injecting fuel downstream, the burner could be ignited at pressures as low as 6 inches of mercury with a spark ignitor.

Combustion was stable over the entire range of equivalence ratios investigated. Rich blowout was never encountered. Lean blowout was encountered only at the higher inlet Mach numbers (0.5 exhaust nozzle) with the 18-inch burner length. Blowout occurred at a burner total pressure of $6\frac{1}{2}$ inches of mercury absolute and an equivalence ratio of approximately 0.2. No lean blowout was observed at the lower inlet Mach numbers (0.4 exhaust nozzle).

An acoustical liner, which was 6 inches long and spaced 1/2 inch from the outer wall, eliminated screech. Liners with closer spacings were unsuccessful. The presence of the liner impaired the burner performance (4 to 6 percentage point drop in combustion efficiency) because of the associated change in fuel distribution. With a larger diameter burner the decrease in combustion efficiency might be less.

Lewis Flight Propulsion Laboratory
    National Advisory Committee for Aeronautics
        Cleveland, Ohio, October 26, 1956

APPENDIX A

SYMBOLS

A	area, ft^2
A_b	area of burner based on 16-inch diameter, ft^2
c_d	discharge coefficient of exhaust nozzle
f/a	combustor fuel-air ratio
$(f/a)'$	ideal combustor fuel-air ratio
$(f/a)_p$	preheater fuel-air ratio
$(f/a)_s$	stoichiometric fuel-air ratio
g	acceleration due to gravity, 32.2 ft/sec^2
M	Mach number
P	total pressure, in. Hg abs
p	static pressure, in. Hg abs
R	gas constant, ft-lb/(lb)(^{o}R)
T	total temperature, ^{o}R
V	velocity, ft/sec
w	combustor-inlet airflow, lb/sec (containing preheater products of combustion)
w_a	airflow to preheater
w_f	fuel flow to combustor, lb/sec
$w_{f,p}$	fuel flow to preheater, lb/sec
w_u	unburned airflow entering combustor, lb/sec
γ	ratio of specific heats
η	combustion efficiency, percent

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ρ density, lb/ft^3

φ engine equivalence ratio, $(f/a)/(f/a)_s$

Subscripts:

1   inlet duct inlet

2   combustor inlet

3   exhaust-nozzle exit

c   cold (i.e., combustor not burning)

h   hot (i.e., combustor burning)

APPENDIX B

CALCULATIONS

Combustor-inlet airflow. - The combustor airflow was measured at the exhaust-nozzle exit for nonburning conditions. Since the combustor entrance duct throat was choked at all times, the combustor-inlet air-flow for a given·inlet pressure was the same for burning and nonburning conditions. The combustor-inlet airflow was calculated from the continuity equation:

$$w = \rho_{3,c} \, c_d \, A_{3,c} \, V_{3,c} \tag{1}$$

Since the exhaust nozzle was always choked, this equation reduces to

$$w = 0.491 \, \frac{P_3 \, A_{3,c} \, c_d}{\sqrt{RT_3}} \sqrt{\gamma g \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{\gamma-1}}} \tag{2}$$

where T_1 and T_3 were assumed equal (nonburning), and a value of 0.975 was used for c_d (ref. 3). Leakage through the engine flanges was negligible.

Combustor fuel-air ratio. - The combustor fuel-air ratio was defined as the ratio of the combustor fuel flow to the unburned air passing through the combustor inlet. The preheater efficiency was almost 100 percent and, therefore, the unburned air entering the combustor was defined as

$$w_u = w_a \left[1 - \frac{(f/a)_p}{(f/a)_s} \right] \tag{3}$$

The combustor fuel-air ratio was then

$$f/a = \frac{w_f}{w_u} = \frac{w_f}{w_a \left[1 - \frac{(f/a)_p}{(f/a)_s} \right]} \tag{4}$$

Since it was more convenient to measure combustor-inlet airflow w rather than airflow to the preheater w_a, the following relation was used:

$$w = (w_a + w_{f,p}) = w_a \left[1 + (f/a)_p \right] \tag{5}$$

Rearrangement and substitution in equation (4) give

$$f/a = \frac{w_f}{w}\left[\frac{1 + (f/a)_p}{1 - \dfrac{(f/a)_p}{(f/a)_s}}\right] \qquad (6)$$

Combustion efficiency. - Combustion efficiency was defined as

$$\eta = \frac{(f/a)'}{f/a}$$

where $(f/a)'$ is the ideal fuel-air ratio which would have produced the same burner pressure P_3 as actually measured.

The ideal fuel-air ratio $(f/a)'$ was determined in the following manner: Since the entrance duct throat was always choked, the inlet airflow could be expressed as

$$w = \rho_{3,c}\,c_{d,c}\,A_{3,c}\,V_{3,c} = \frac{\rho_{3,h}\,c_{d,h}\,A_{3,h}\,V_{3,h}}{1 + \dfrac{w_f}{w}} \qquad (7)$$

Using equation (7) and since $M_3 = 1$, $P_{3,h}$ and $P_{3,c}$ become:

$$P_{3,h} = \frac{w\left(1 + \dfrac{w_f}{w}\right)}{0.491\,A_{3,h}\,c_{d,h}}\sqrt{\frac{R_h\,T_{3,h}}{\gamma_h g}}\;\sqrt{\left(\frac{\gamma_h + 1}{2}\right)^{\frac{\gamma_h+1}{\gamma_h-1}}} \qquad (8)$$

and also

$$P_{3,c} = \frac{w}{0.491\,A_{3,c}\,c_{d,c}}\sqrt{\frac{R_c\,T_{3,c}}{\gamma_c g}}\;\sqrt{\left(\frac{\gamma_c + 1}{2}\right)^{\frac{\gamma_c+1}{\gamma_c-1}}} \qquad (9)$$

if it is assumed that $T_1 = T_{3,c}$, $c_{d,h} = c_{d,c}$, and $A_{3,c} = A_{3,h}$, the following relation is obtained:

$$\frac{P_{3,h}}{P_{3,c}} = \left(1 + \frac{w_f}{w}\right)\sqrt{\frac{T_{3,h}}{T_1}}\;\sqrt{\frac{\left(\dfrac{\gamma_h + 1}{2}\right)^{\frac{\gamma_h+1}{\gamma_h-1}}\left(\dfrac{R}{\gamma}\right)_h}{\left(\dfrac{\gamma_c + 1}{2}\right)^{\frac{\gamma_c+1}{\gamma_c-1}}\left(\dfrac{R}{\gamma}\right)_c}} \qquad (10)$$

Equation (10) was evaluated for various combustor fuel-air ratios by using theoretical combustion charts which included effects of dissociation to find $T_{3,h}$. These data were then plotted as $(f/a)'$ against $P_{3,h}/P_{3,c}$ for a combustor-inlet temperature T_1 of 1100° R. From this plot, the theoretical fuel-air ratio $(f/a)'$ could be obtained for each value of $P_{3,h}/P_{3,c}$ measured at the exhaust-nozzle exit.

The combustion efficiency as defined in this section is not a chemical combustion efficiency such as a heat-balance or enthalpy-rise method would indicate. The combustor efficiency based on total-pressure measurement is, however, more representative of over-all engine performance, in view of the fact that it indicates how effectively the fuel is being used to provide thrust potential rather than how completely the fuel is being burned.

Combustion-chamber inlet Mach number. - The combustion-chamber inlet Mach number was calculated by using the engine-inlet airflow w, the static pressure at the combustor inlet p_2, the engine-inlet total temperature T_1, and the area at the combustor inlet A_2 (157 sq in.).

REFERENCES

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2. Dangle, E. E., and Kerslake, William R.: Experimental Evaluation of Gaseous Hydrogen Fuel in a 16-Inch-Diameter Ram-Jet Engine. NACA RM E55J18, 1955.

3. Grey, Ralph E., Jr., and Wilsted, H. Dean: Performance of Conical Jet Nozzles in Terms of Flow and Velocity Coefficients. NACA Rep. 933, 1949. (Supersedes NACA TN 1757.)

Line blanked off

Inlet-air line

Combustion-type preheater

Supersonic nozzle

Second throat

Exhaust line

Water spray

Surge tank

Screen

Second throat blocked

16-inch ram-jet combustor

Periscope tube

CD-5359
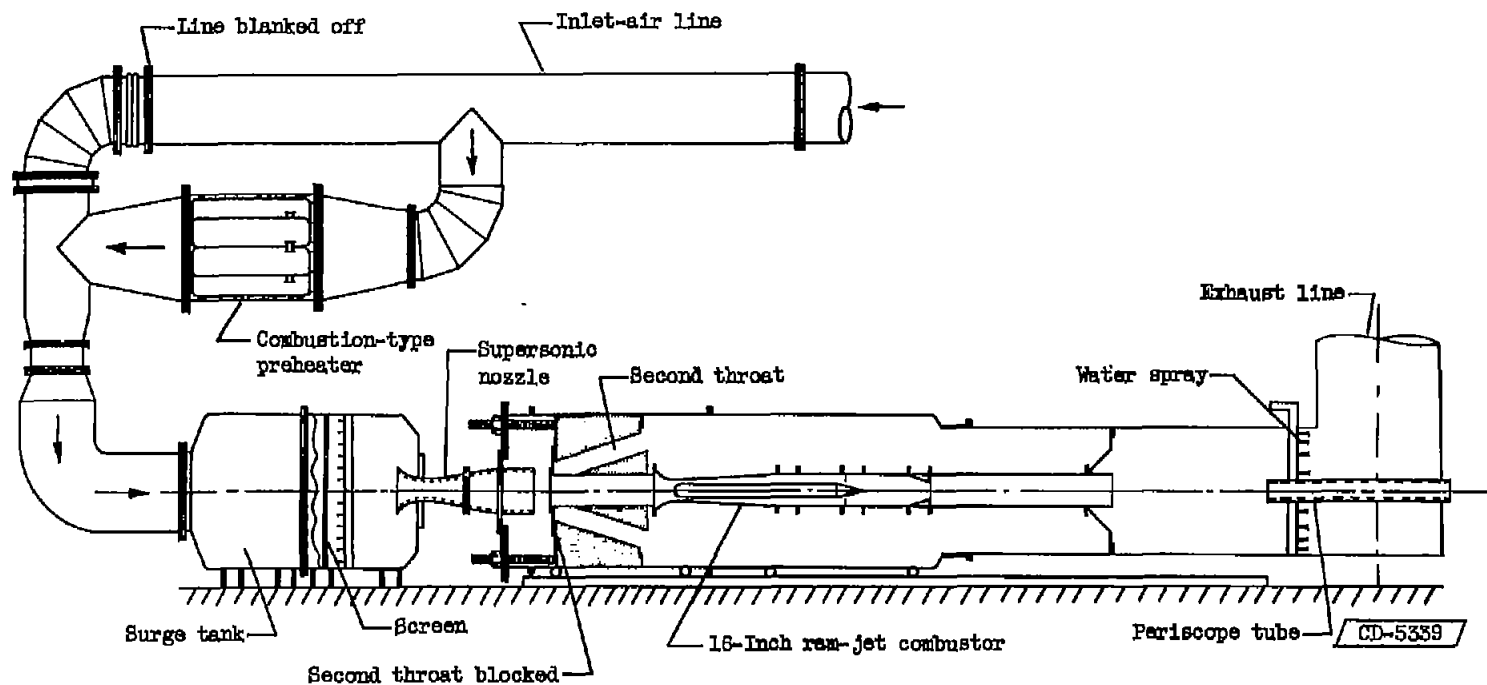
Figure 1. - Direct-connect installation of 16-inch-diameter ram-jet combustor in free-jet facility.

Station 1 (Entrance duct inlet)   2 (Burner inlet)   3 (Nozzle exit)

Entrance duct

Fuel injectors

Spool pieces

Water jacket

Water-cooled rake

Entrance duct throat

Airflow direction

8"

6"

16"

20"

12"

CD-5391

Burner length
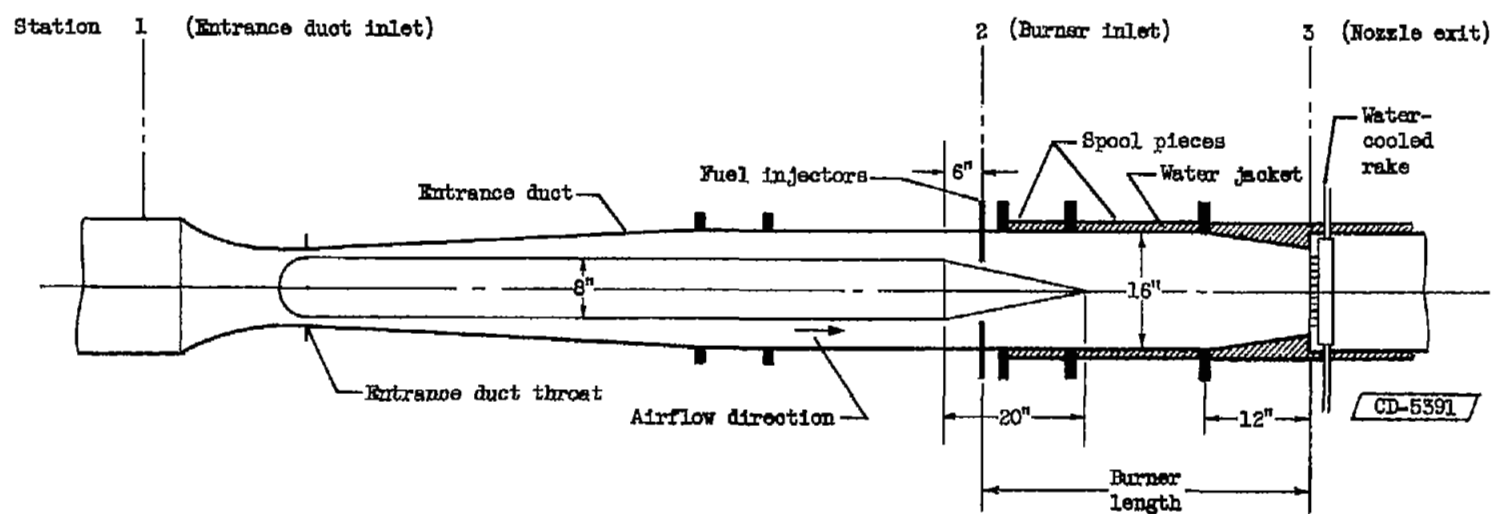
Figure 2. - Schematic diagram of 16-inch ram-jet combustor.
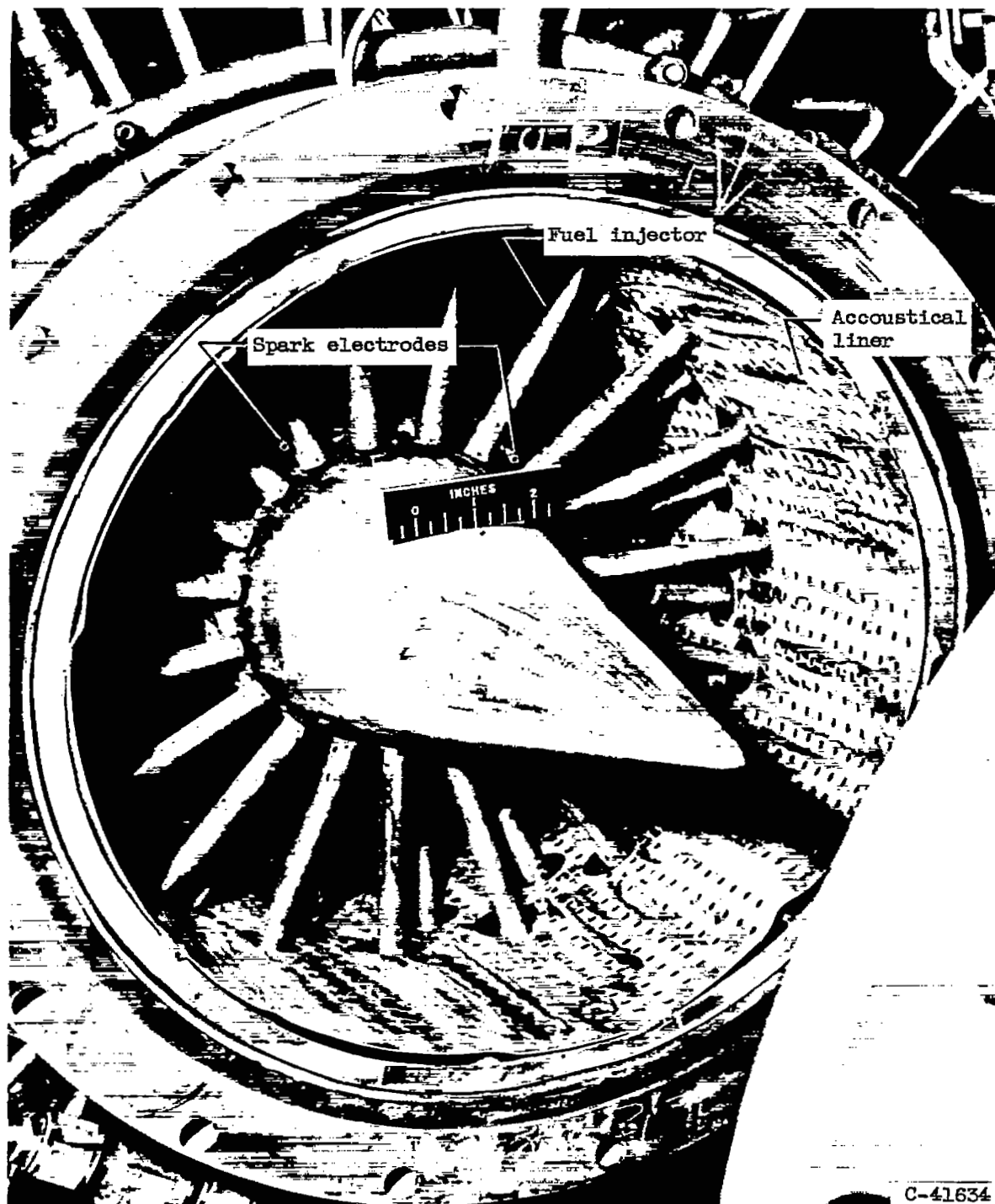
Figure 3. - Combustion chamber at fuel-injector station showing spark electrodes and screech liner after 30 minutes of operation.
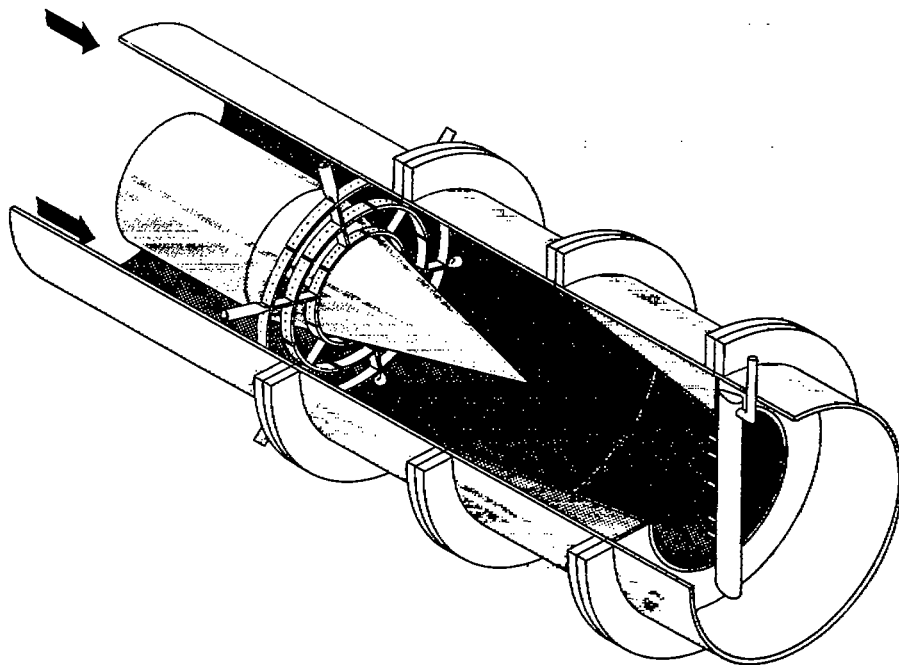
(a) Concentric-ring system.
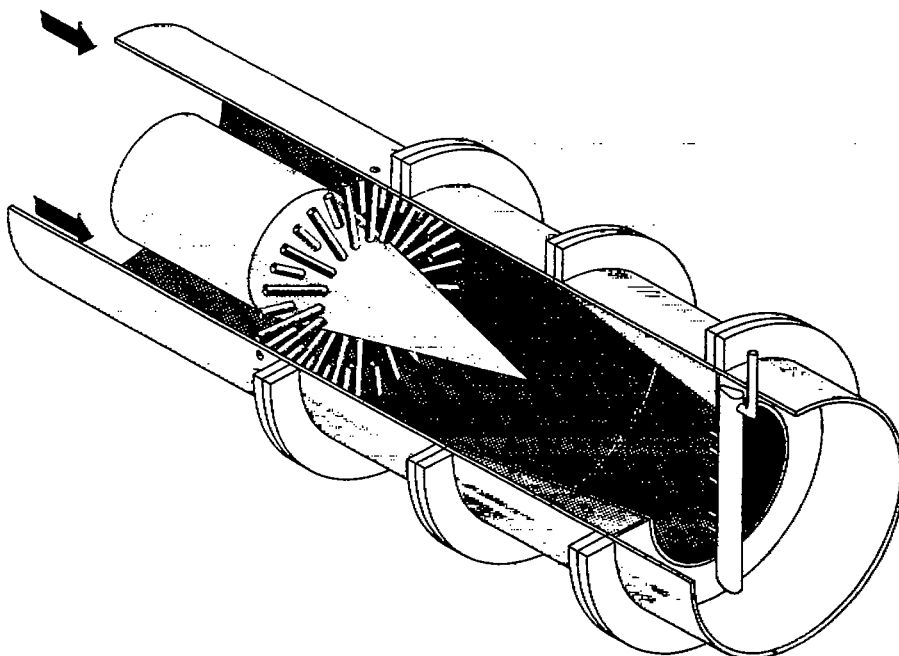
(b) Radial system.   CD-5337

Figure 4. - Concentric-ring and radial fuel injector systems.
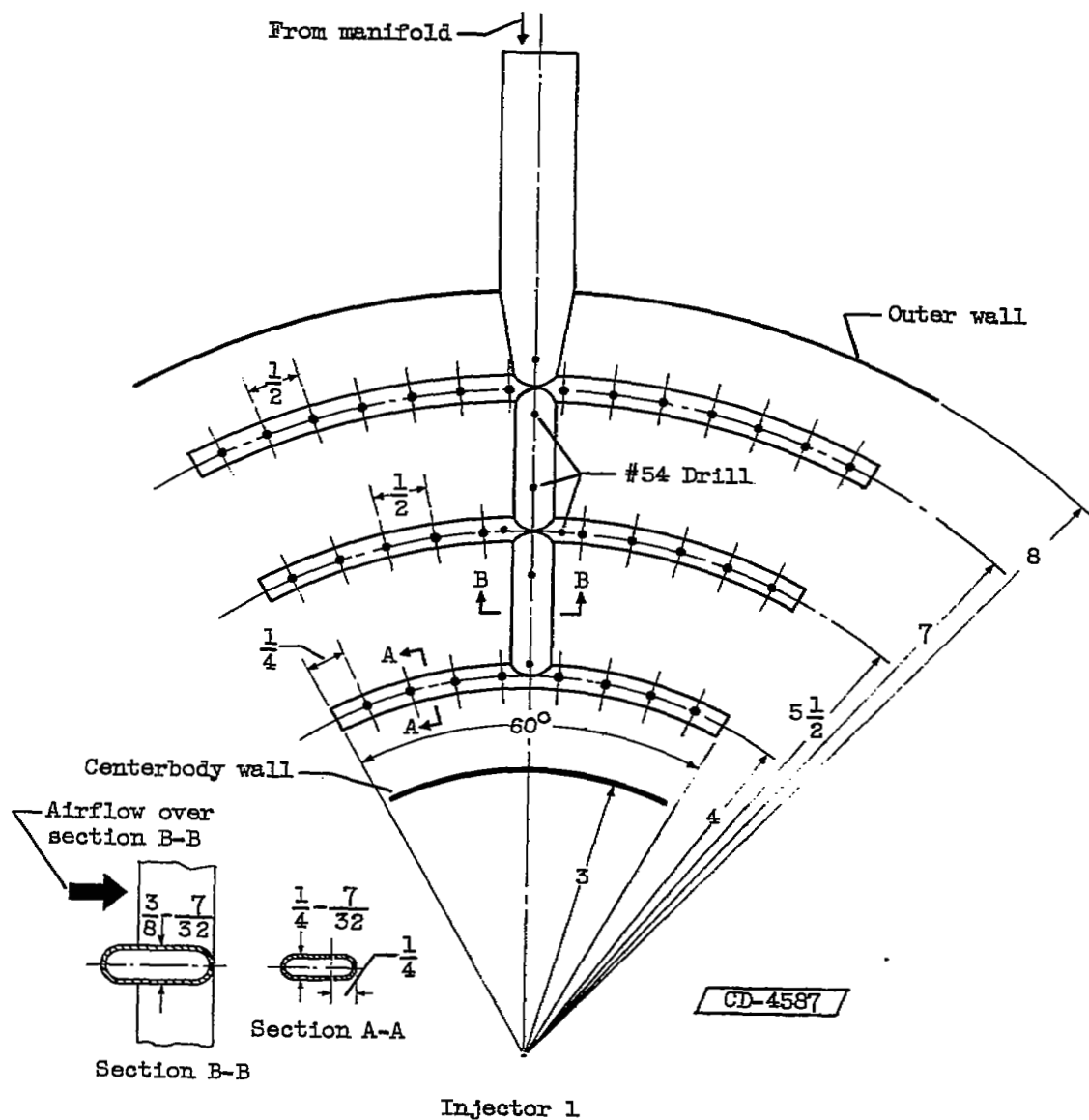
Injector 1

(a) Concentric-ring fuel injector.

Figure 5. – Schematic diagrams of fuel-injector designs.
(All dimensions are in inches except as noted.)

Injector 2

Injector 3

(a) 30°   (d)   Single orifice injectors,
               0.055-in. diam. orifices.

(b)   (e)

(c)   (f)   Double orifice injectors,
               0.033-in. diam. orifices.

Section A-A

0.033-in. diam.
fuel orifices.

Section B-B

CD-5338
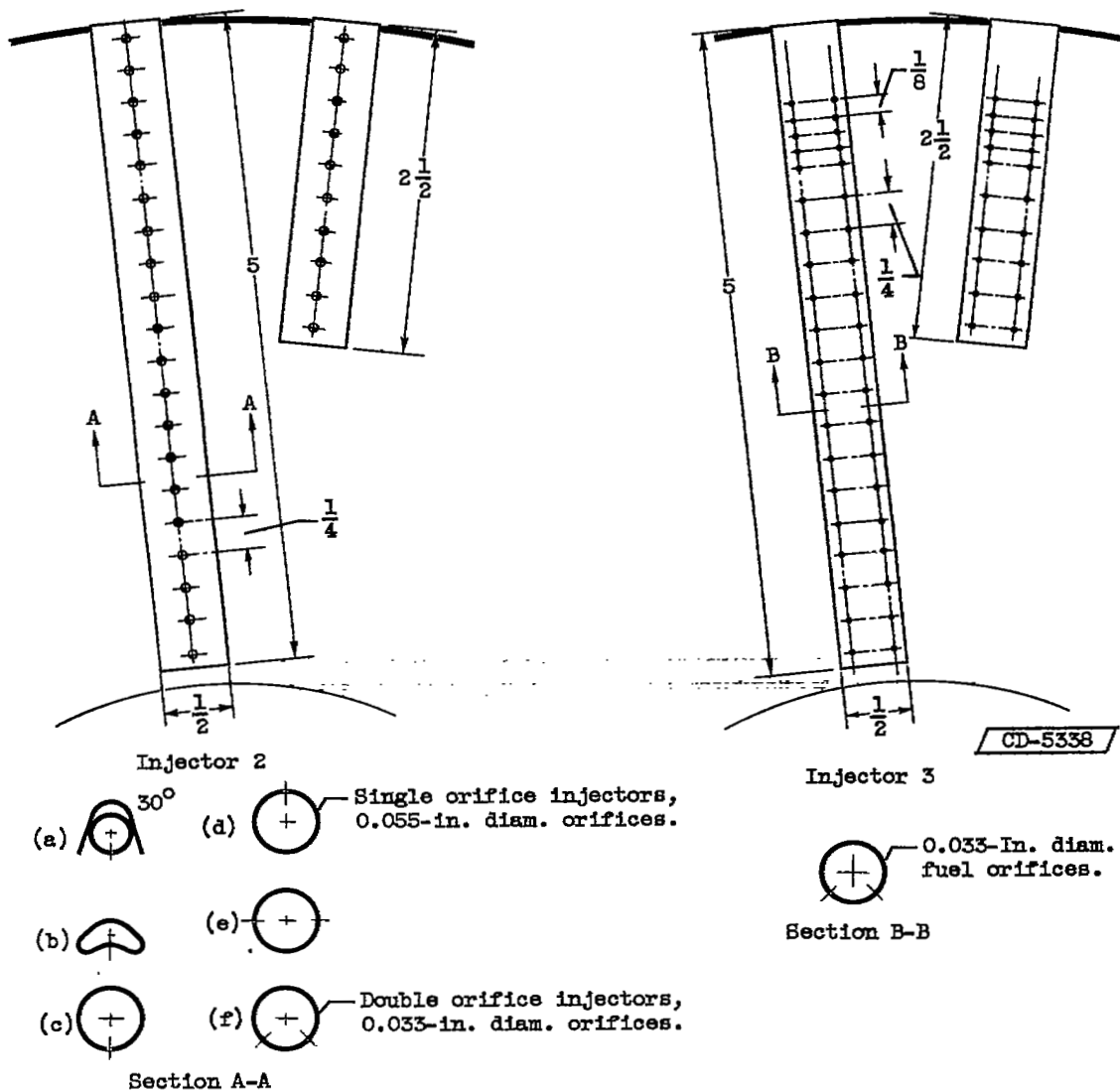
(b) Radial fuel injectors.

Figure 5. - Continued. Schematic diagrams of fuel injector designs.
(All dimensions are in inches except as noted.)

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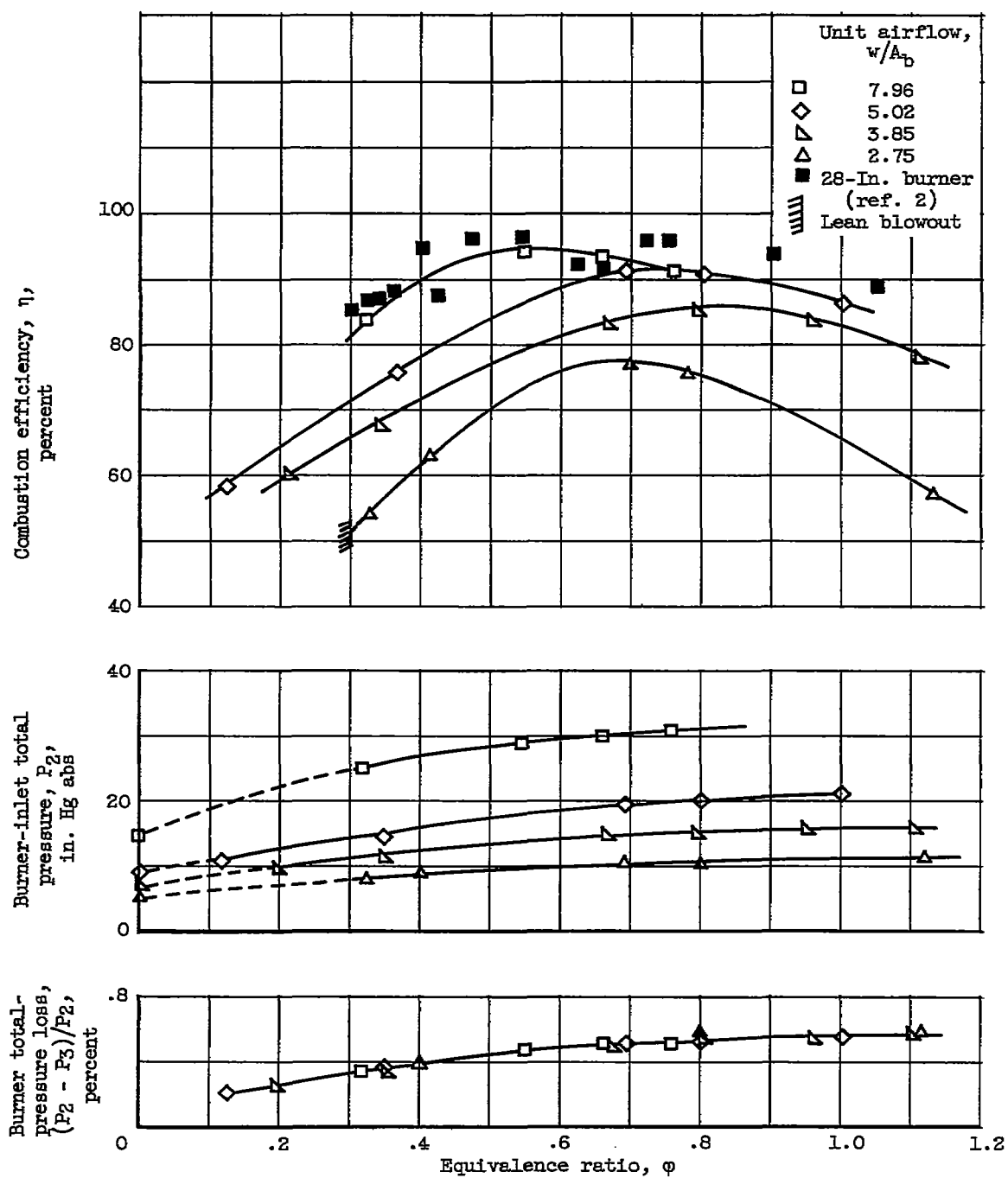
(a) Burner length, 26 inches.

Figure 6. - General performance characteristics of configuration A.

(b) Burner length, 18 inches.
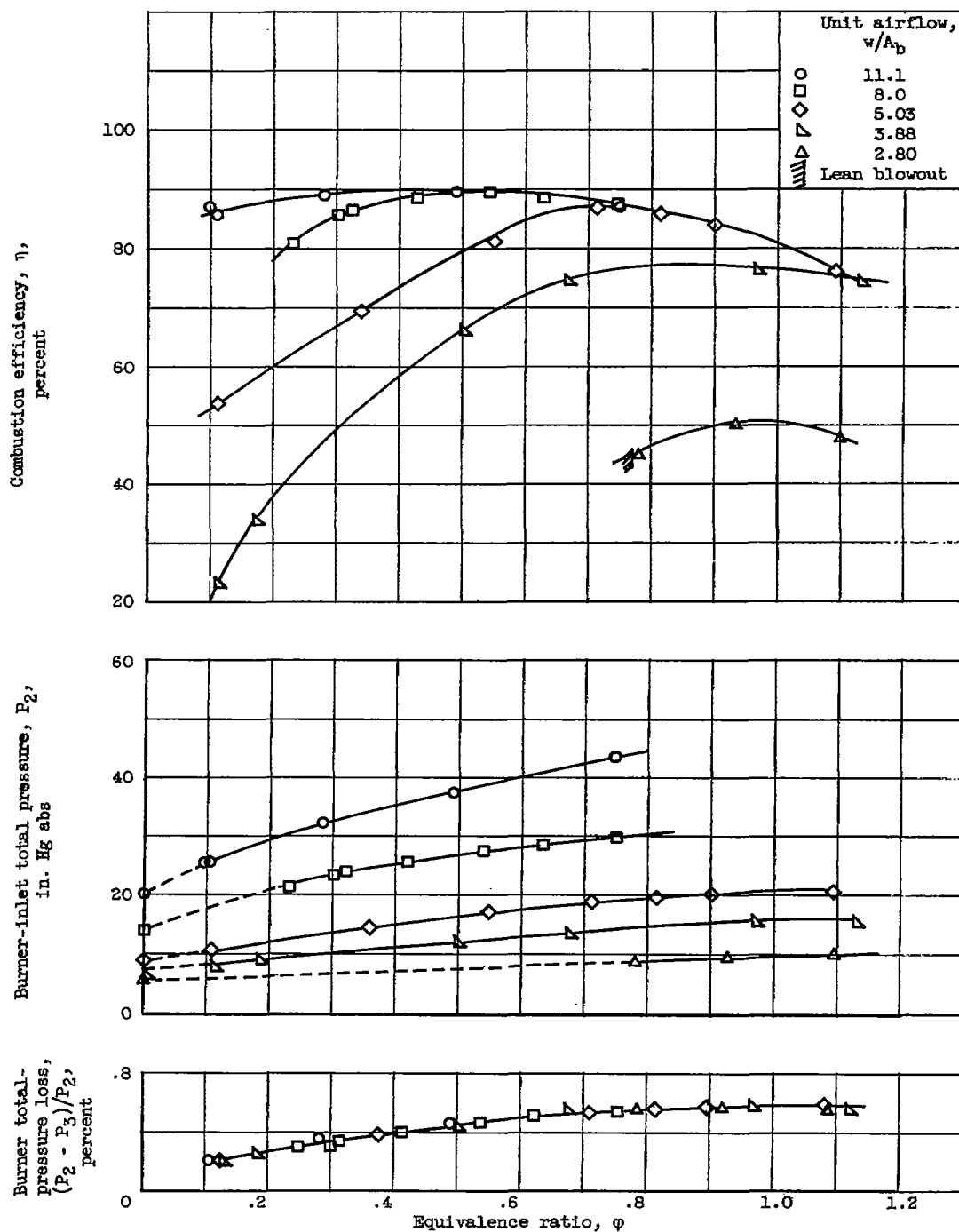
Figure 6. - Concluded. General performance characteristics of configuration A.

(a) Unit airflow, approximately 5.1 pounds per second per square foot.

(b) Unit airflow, approximately 3.9 pounds per second per square foot.

(c) Unit airflow, approximately 2.8 pound per second per square foot.
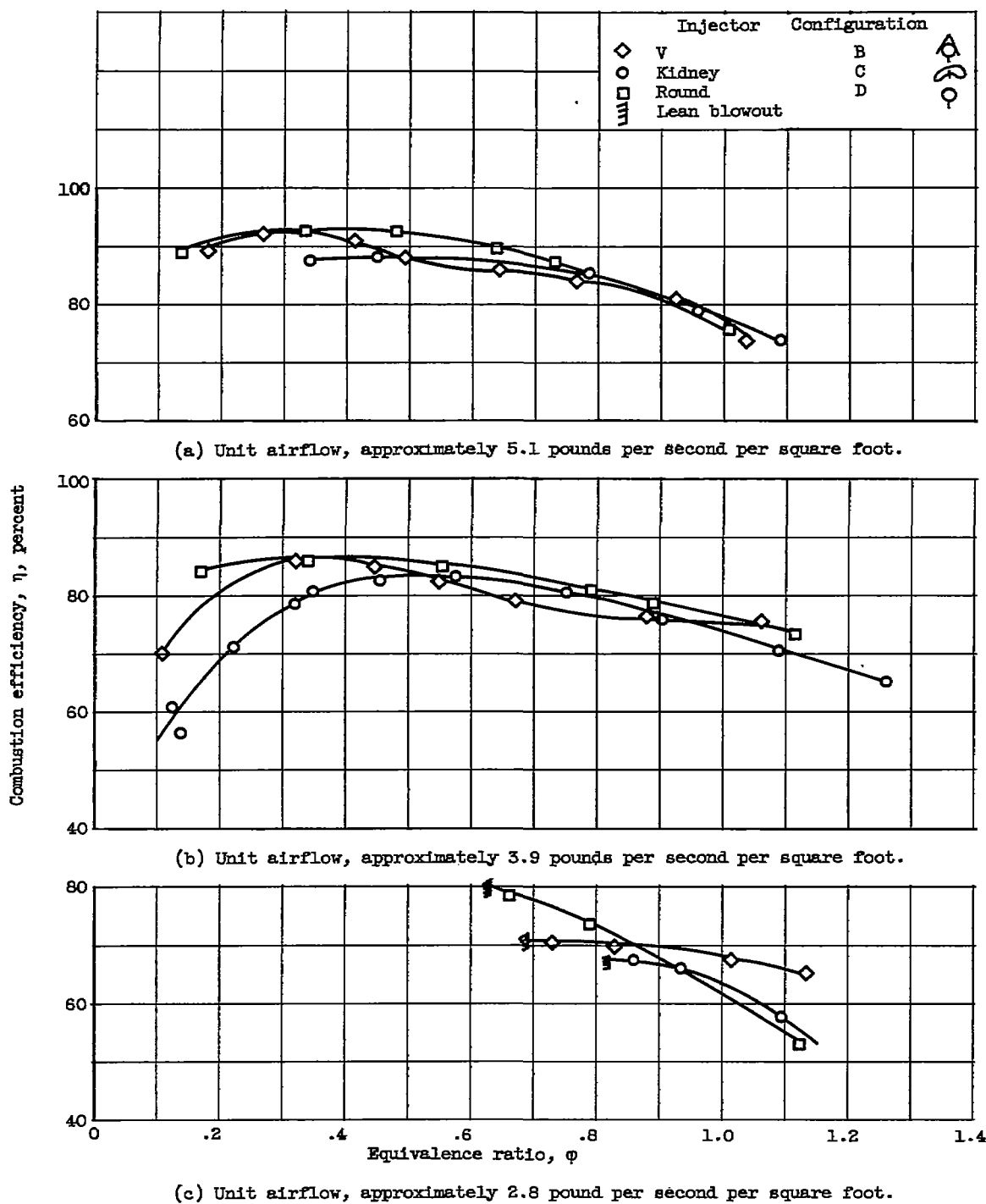
Figure 7. - Effect of injector shape on combustion efficiency. Burner length, 18 inches.
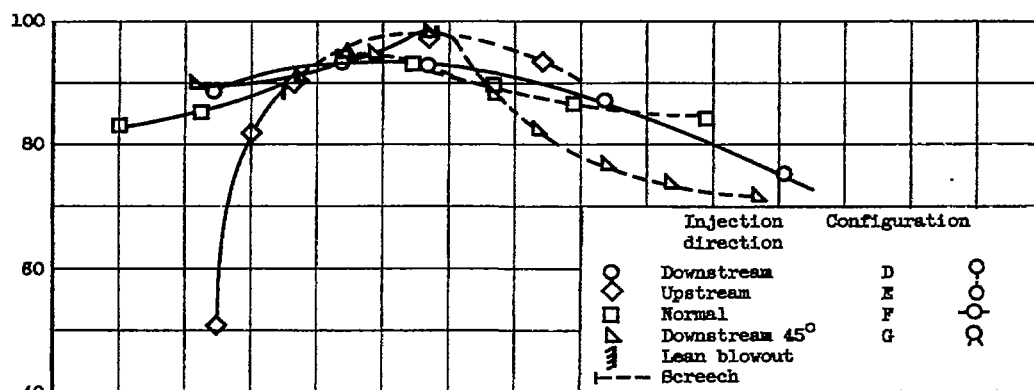
(a) Unit airflow, approximately 5.1 pounds per second per square foot.
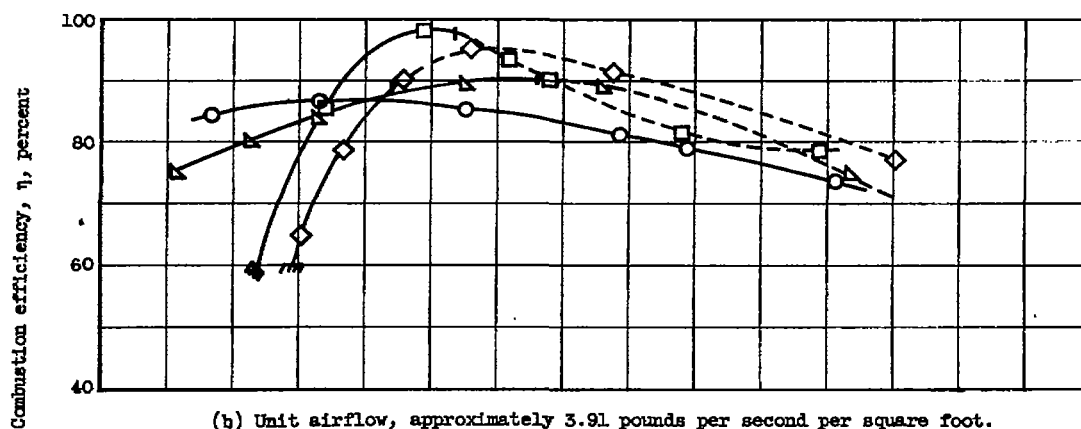
(b) Unit airflow, approximately 3.91 pounds per second per square foot.
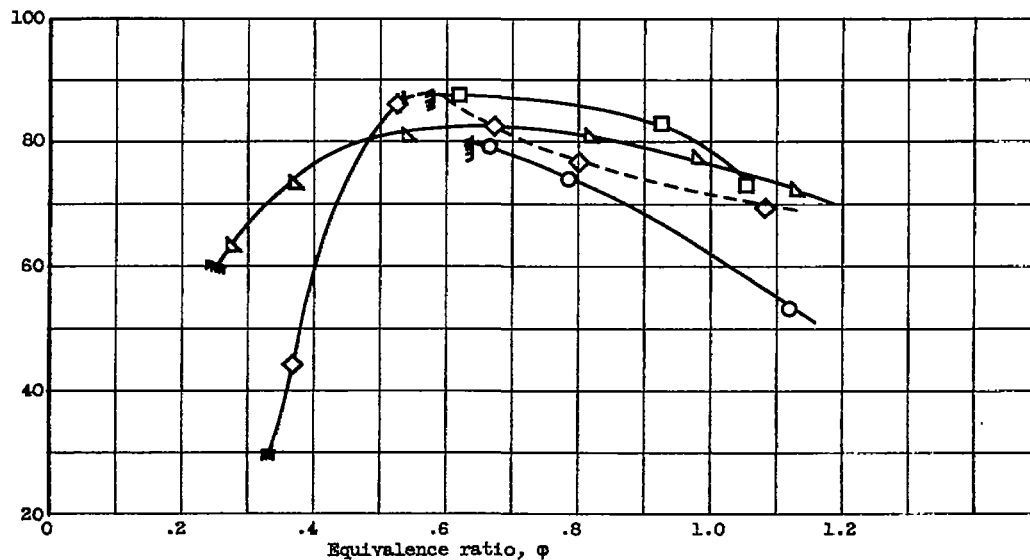
(c) Unit airflow, approximately 2.75 pounds per second per square foot.

Figure 8. - Effect of injection direction on combustion efficiency. Burner length, 18 inches.

CP-4 back   4210

Combustion efficiency, η, percent

	Injector	Configuration	
O	Not staggered	G	
□	Staggered	H	
⫸	Lean blowout		
⊢---	Screech		

(a) Unit airflow, approximately 5.1 pounds per second per square foot.

(b) Unit airflow, approximately 3.9 pounds per second per square foot.

Equivalence ratio, φ

(c) Unit airflow, approximately 2.7 pounds per second per square foot.
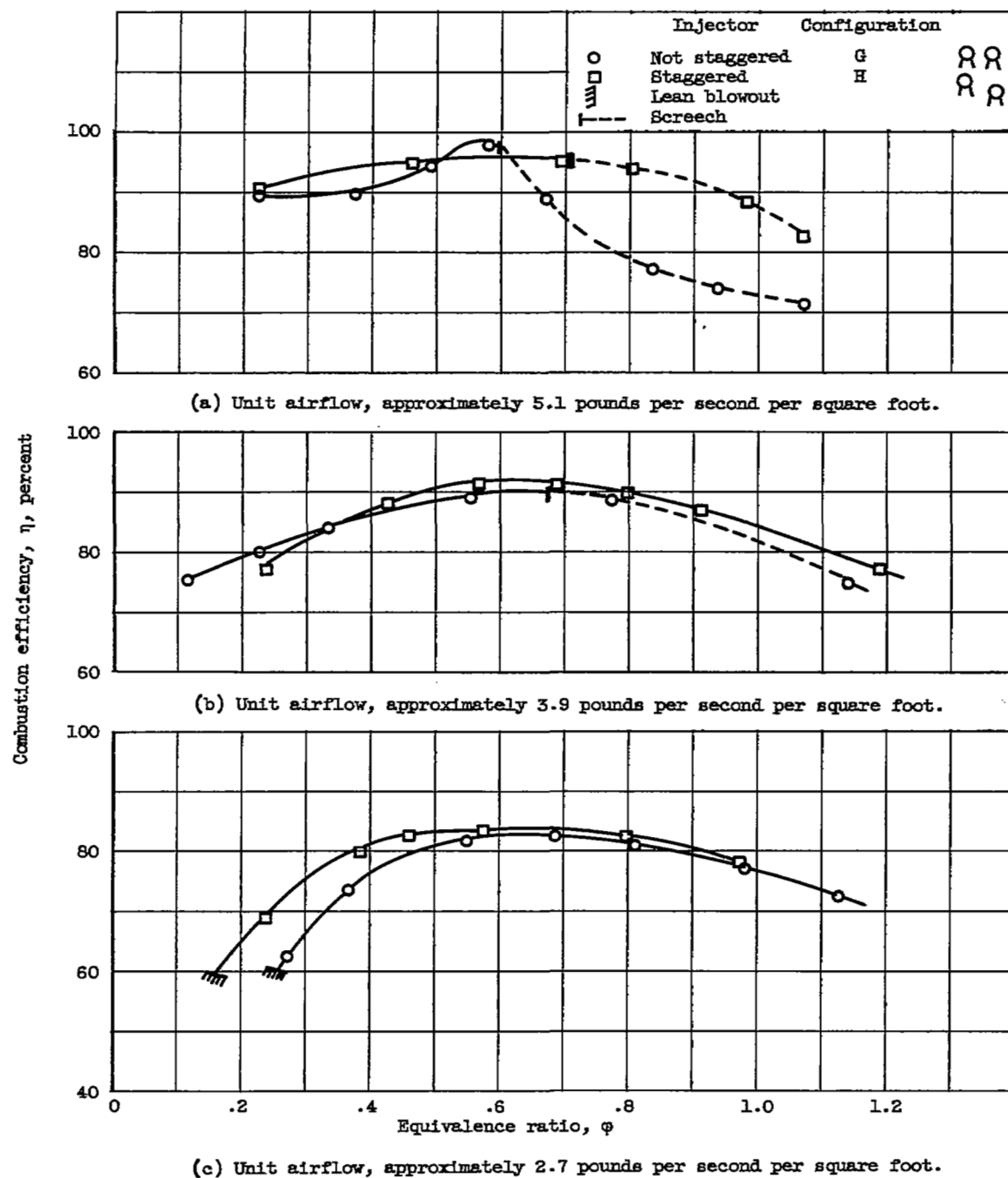
Figure 9. - Effect of staggering injectors on screech and combustion efficiency. Burner length, 18 inches.

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(a) Unit airflow, approximately 5.0 pounds per second per square foot.

(b) Unit airflow, approximately 3.8 pounds per second per square foot.

(c) Unit airflow, approximately 2.7 pounds per second per square foot.
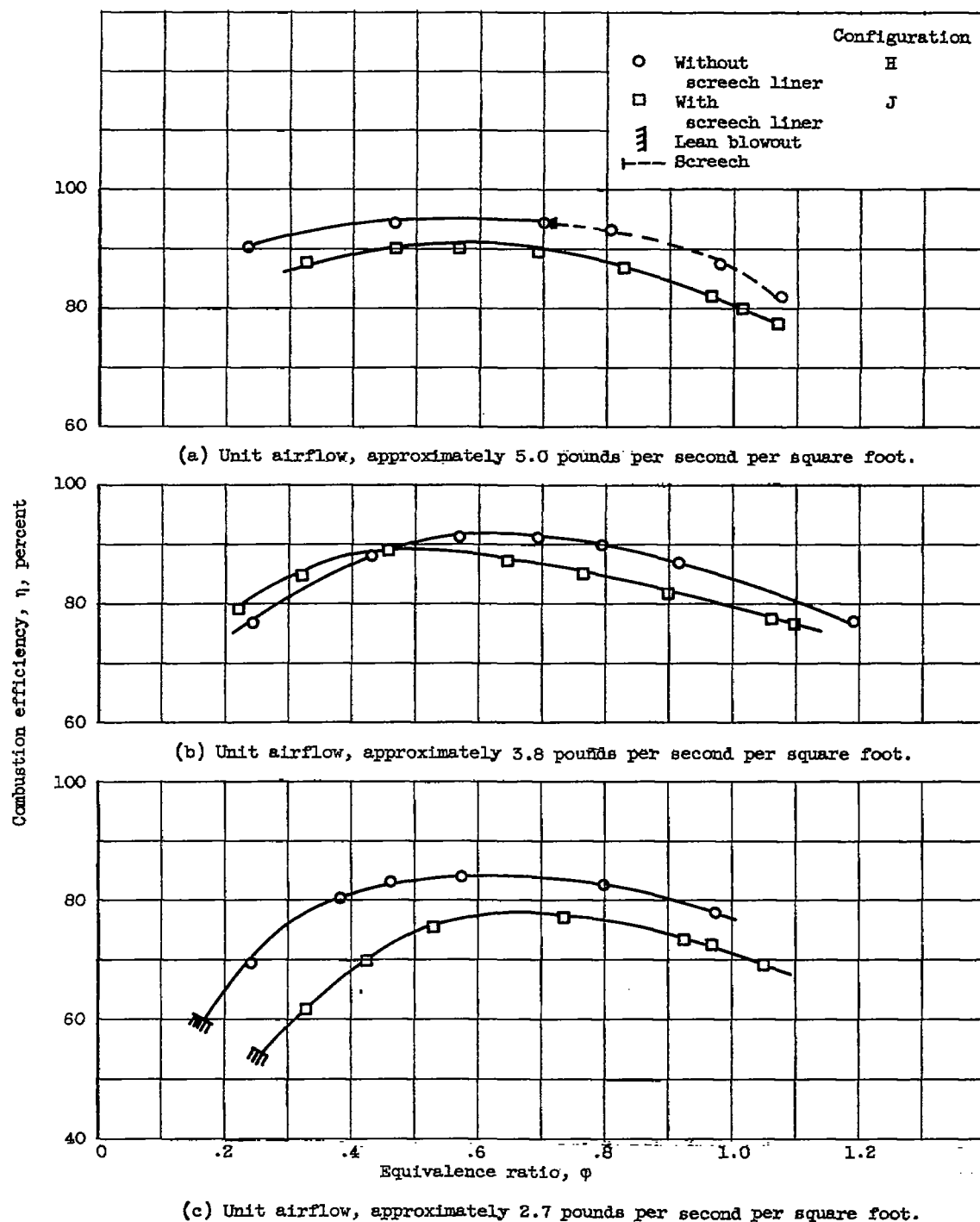
Figure 10. - Effect of screech liner on combustion efficiency. Burner length, 18 inches.

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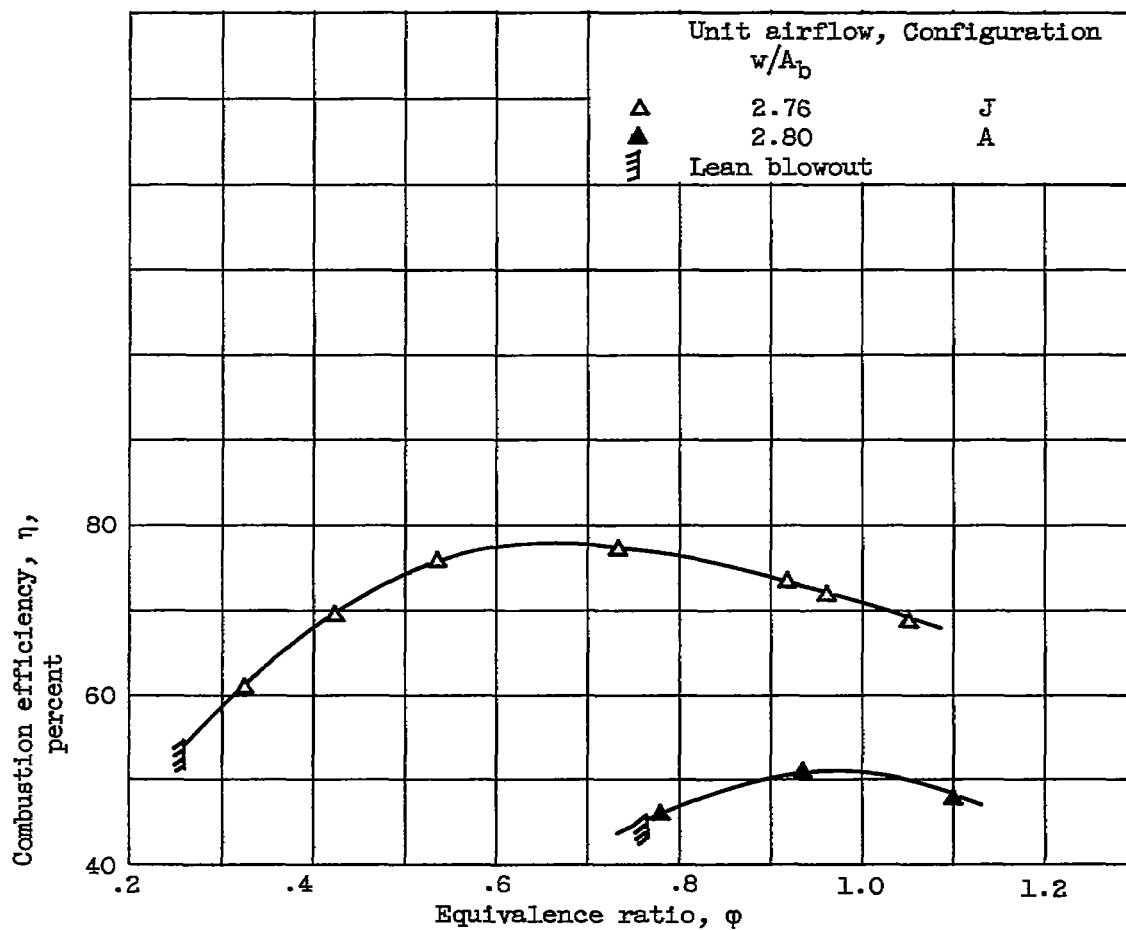
Figure 11. - Comparison of configuration J with configuration A.
   Burner length, 18 inches.
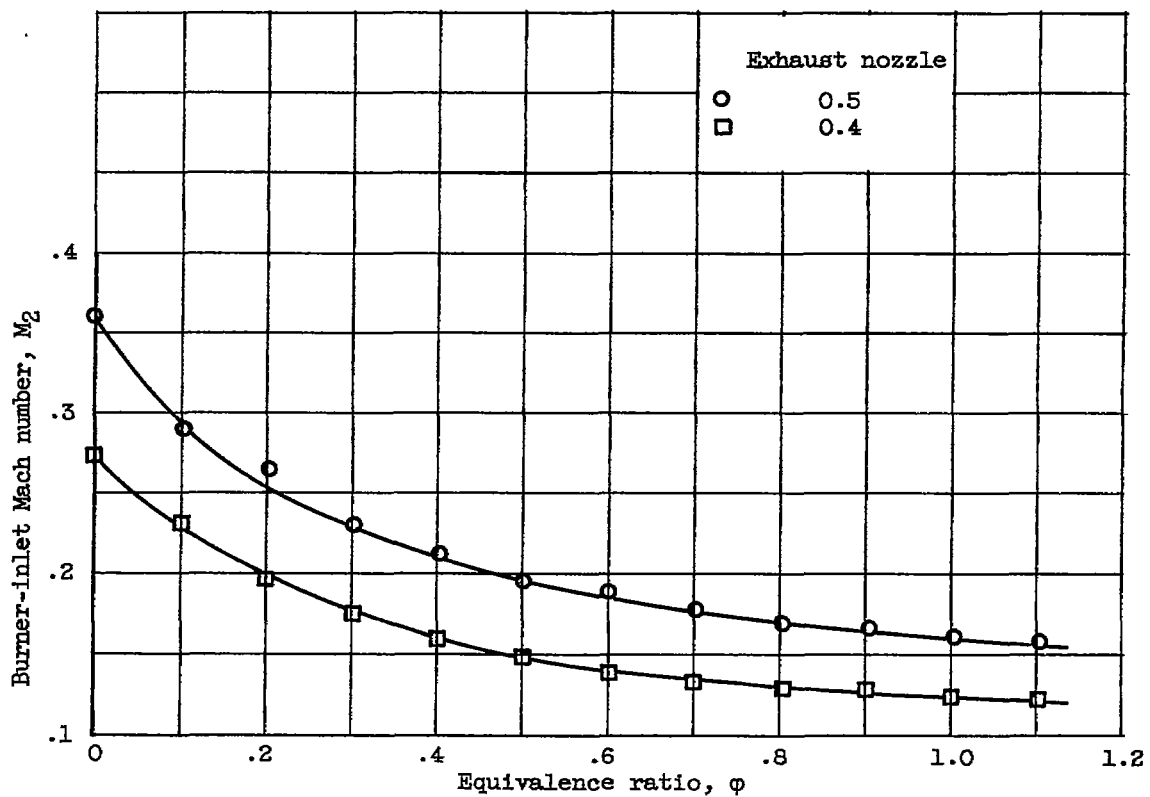
Figure 12. - Burner-inlet Mach number variation with 0.5 and 0.4 exhaust nozzle.
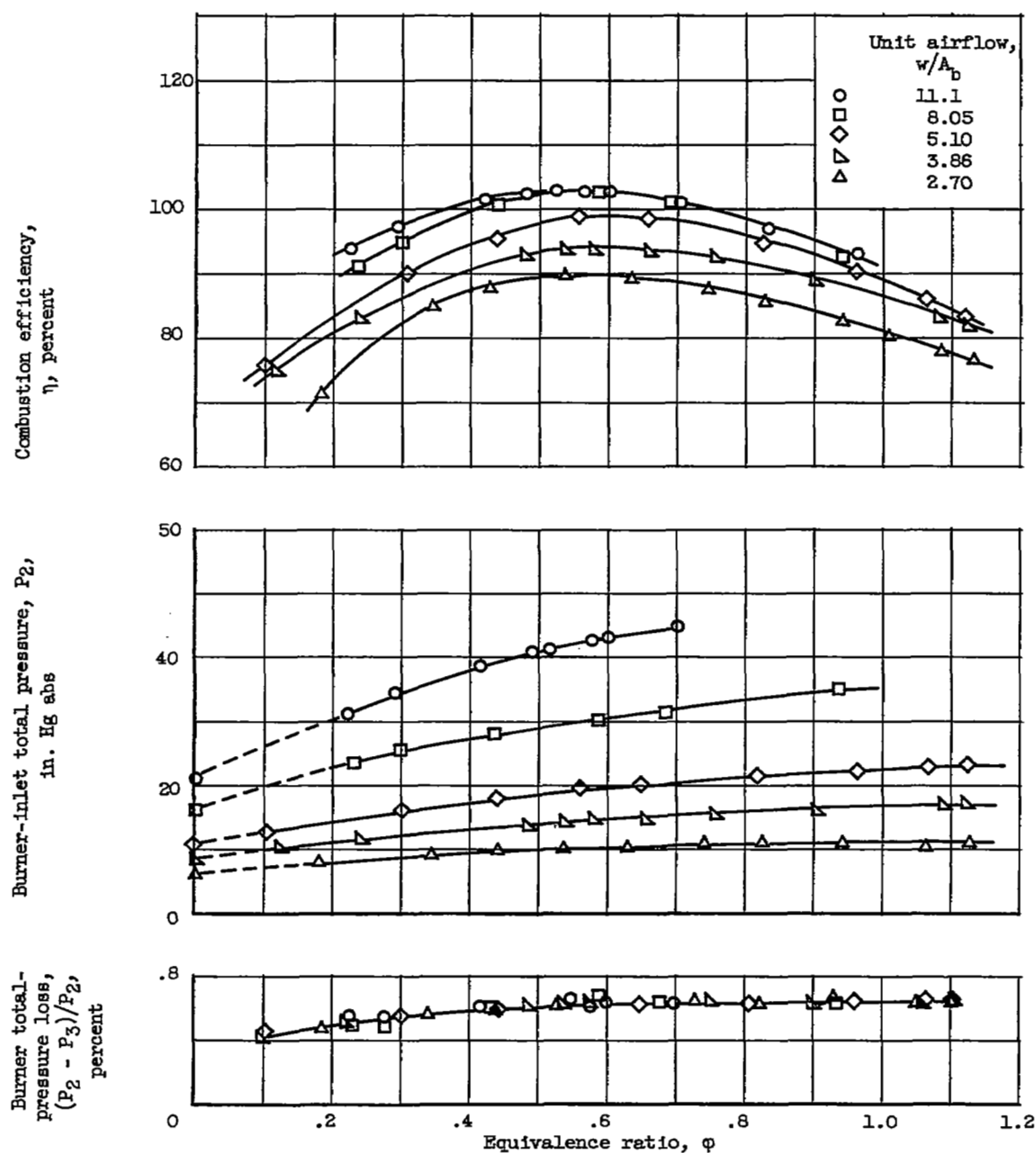
(a) Burner length, 44 inches; 0.5 exhaust nozzle.

Figure 13. - General performance characteristics of configuration J.
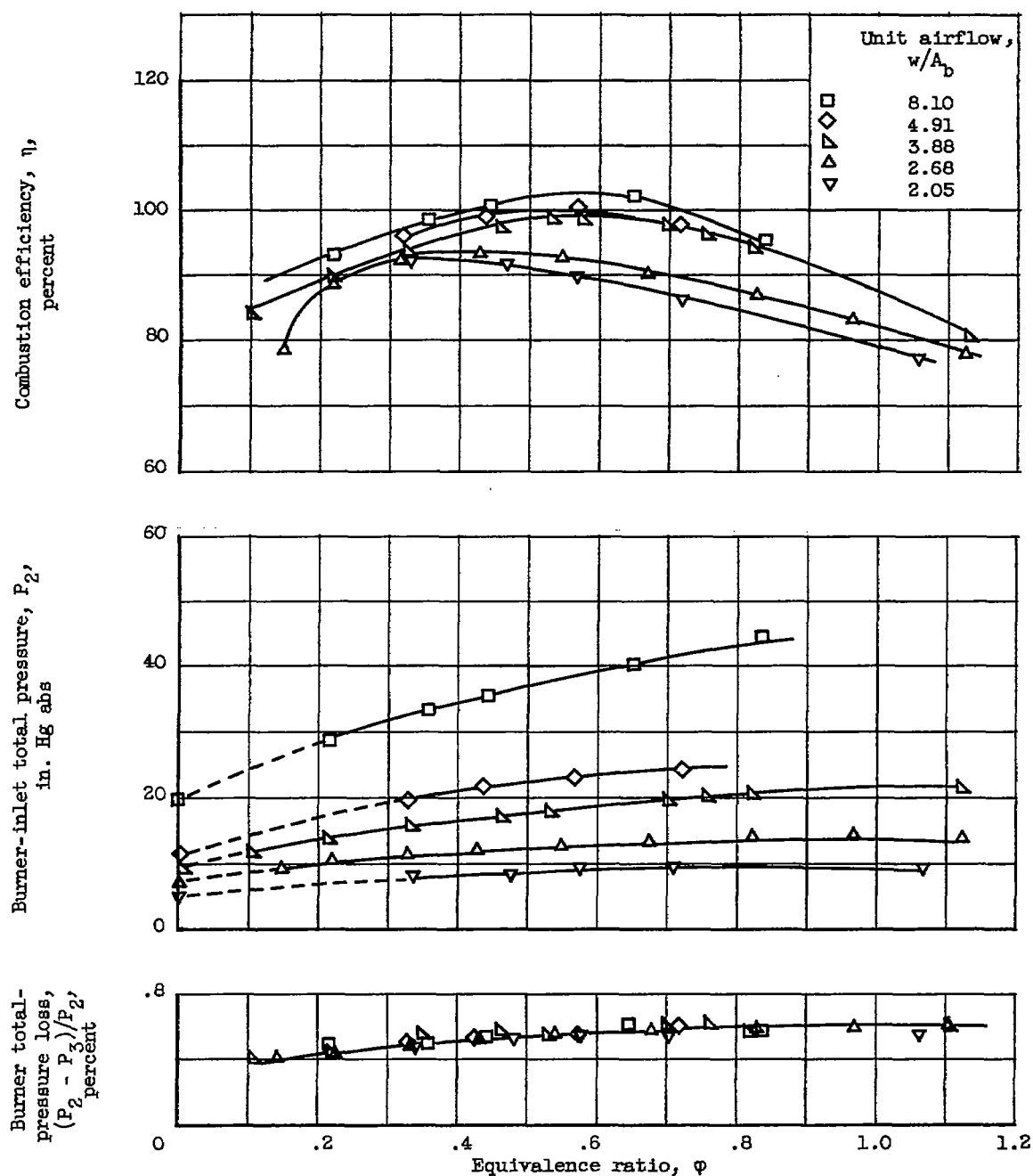
(b) Burner length, 44 inches; 0.4 exhaust nozzle.

Figure 13. - Continued. General performance characteristics of
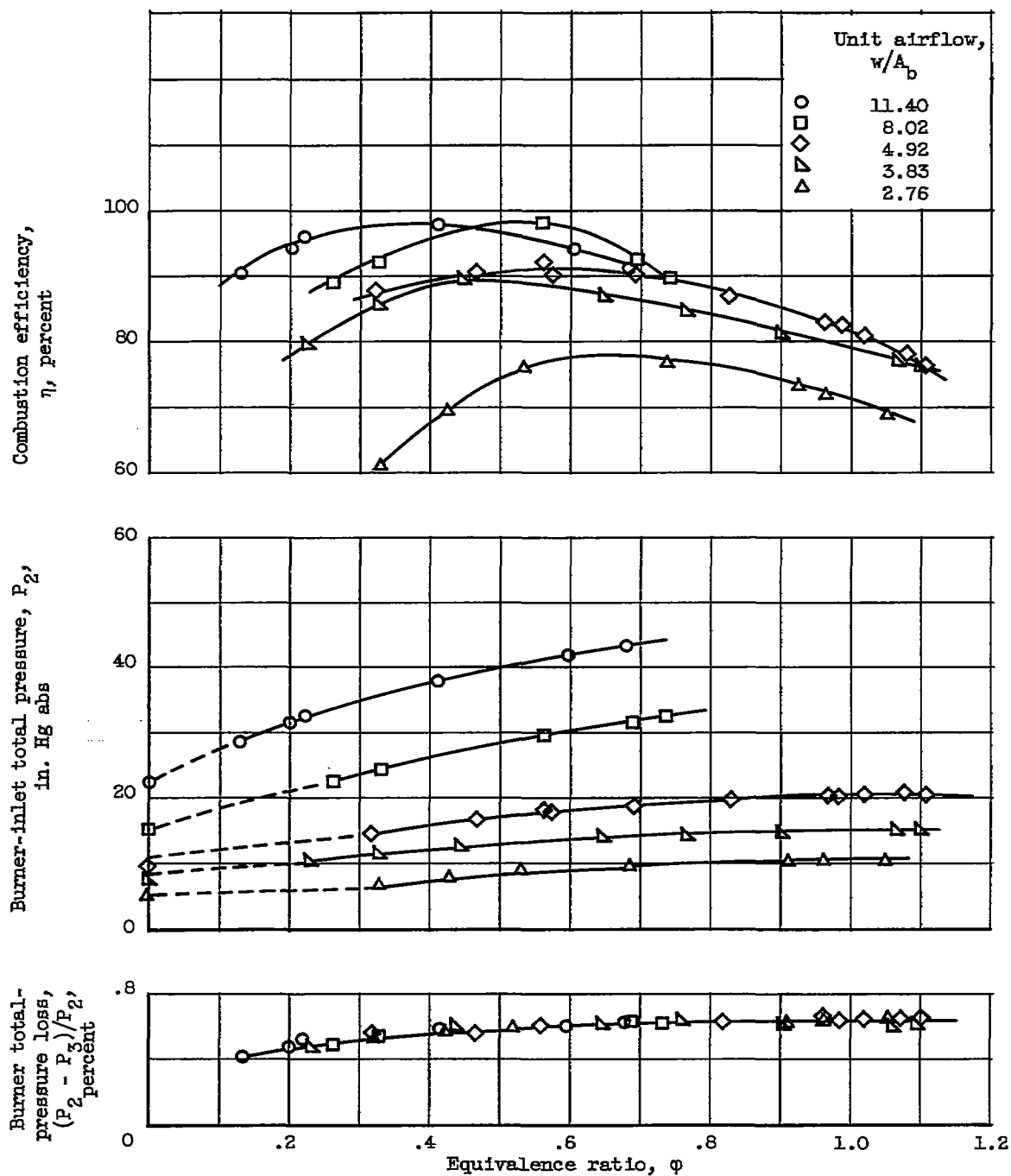configuration J.
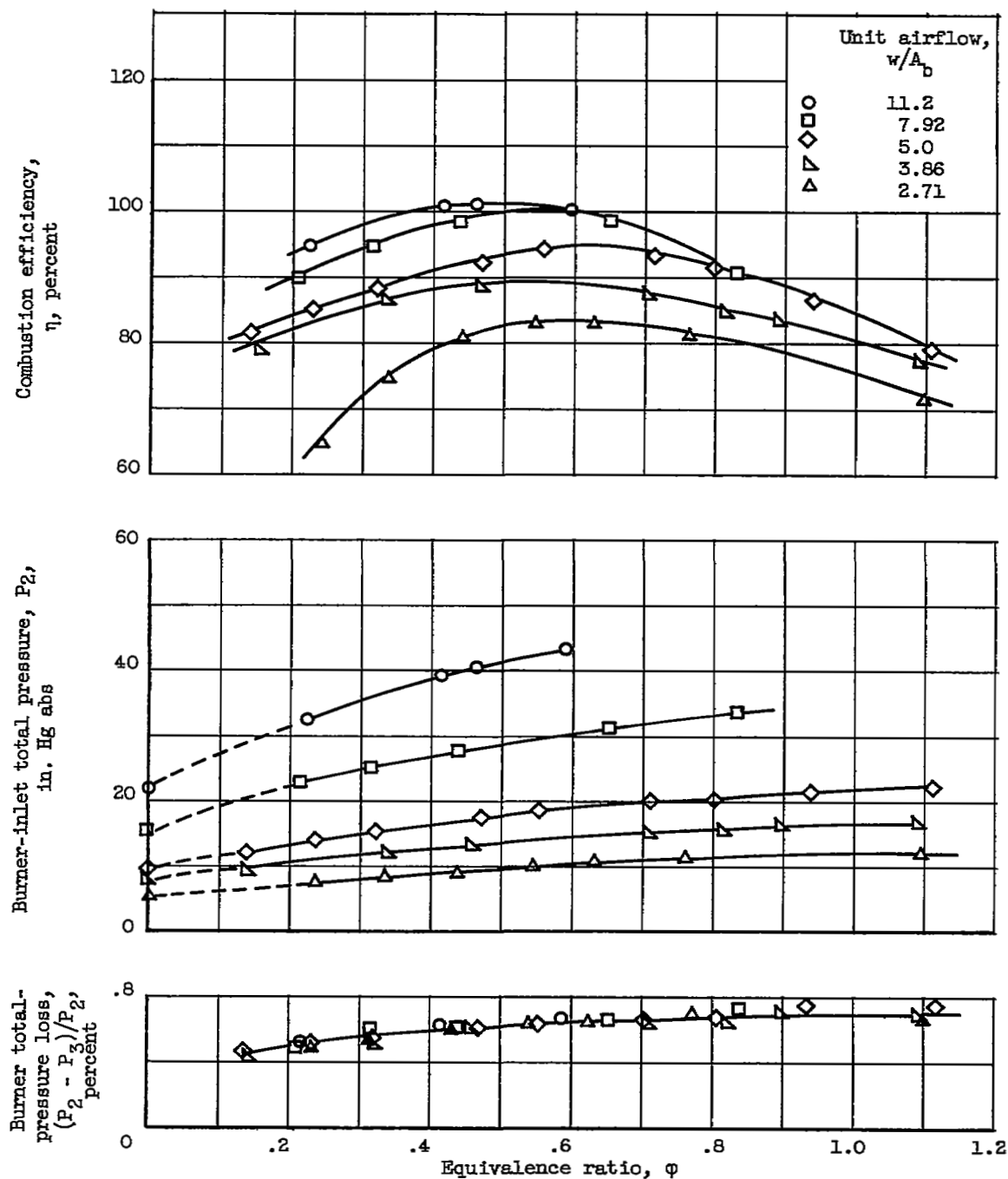
(c) Burner length, 26 inches; 0.5 exhaust nozzle.

Figure 13. - Continued. General performance characteristics of
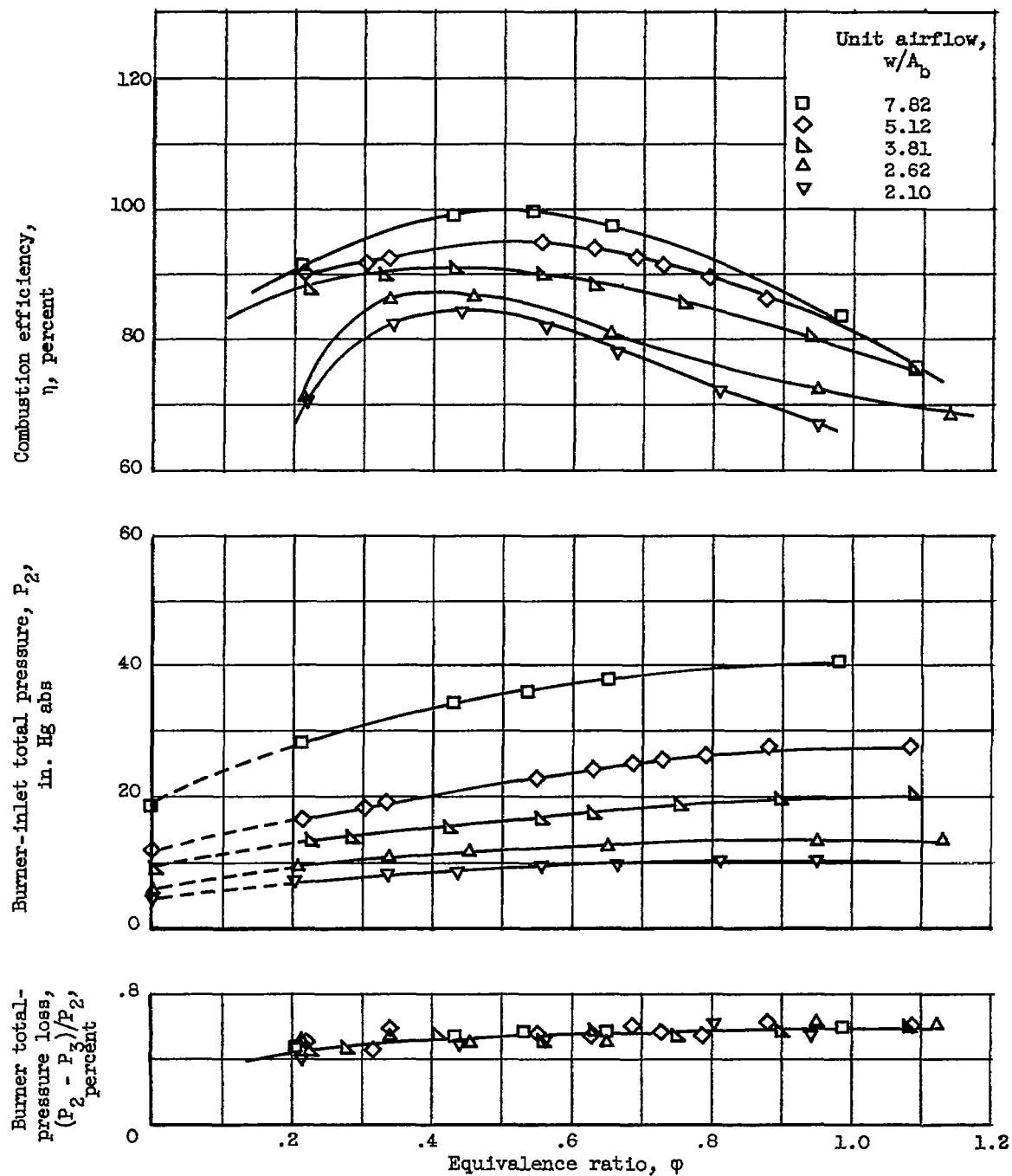   configuration J.

NACA RM E56J08
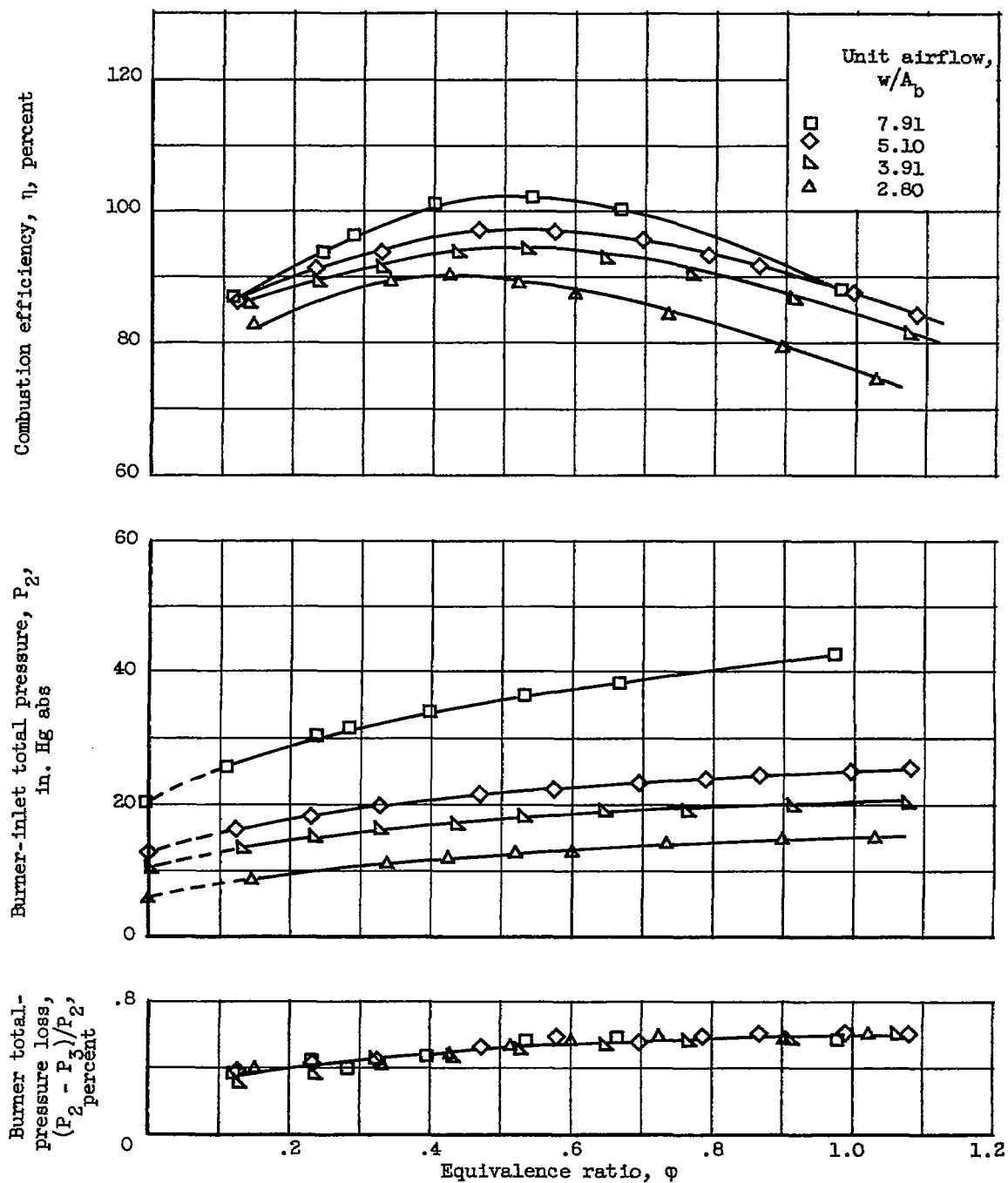
(d) Burner length, 26 inches; 0.4 exhaust nozzle.

Figure 13. - Continued. General performance characteristics of configuration J.
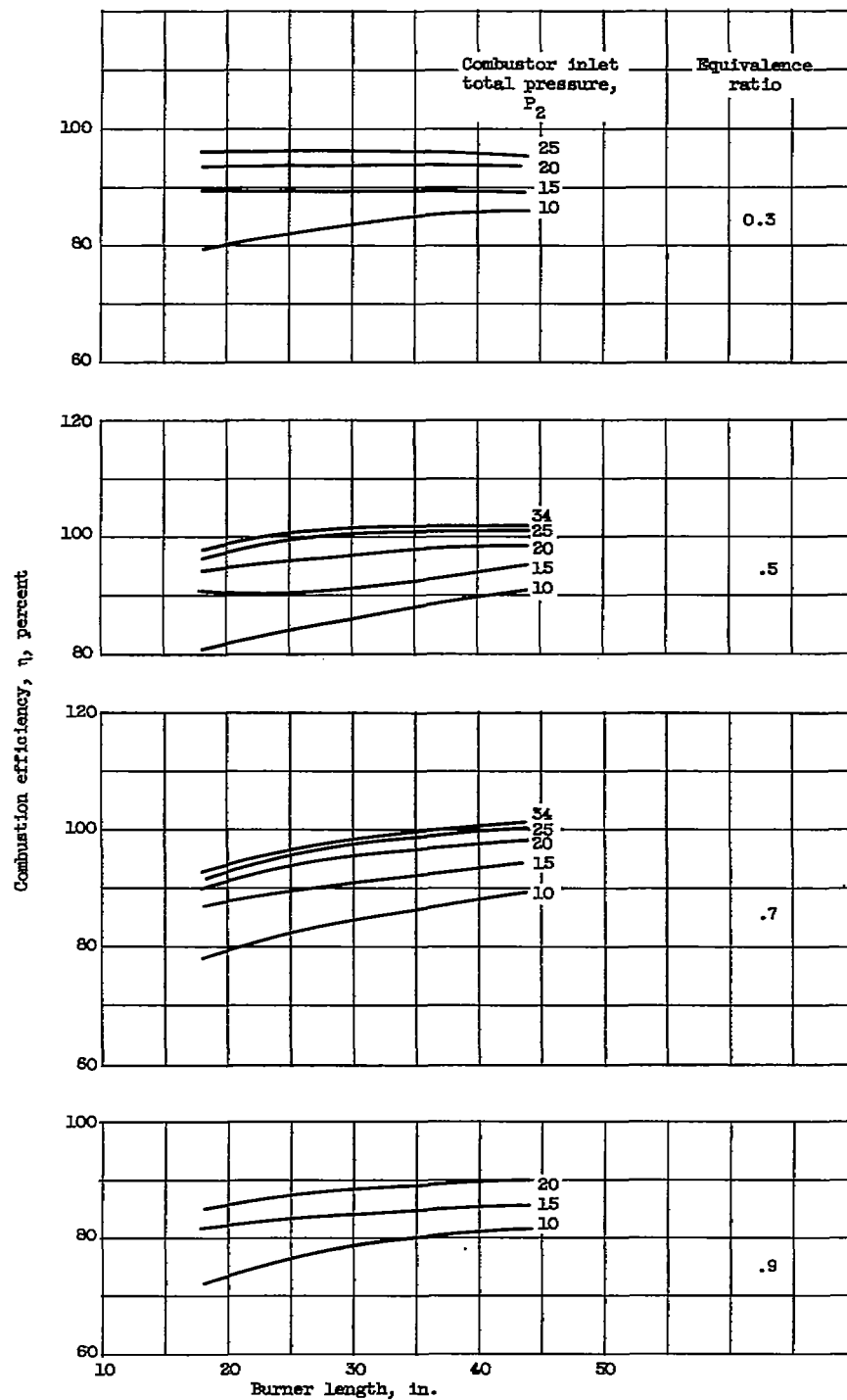
(e) Burner length, 18 inches; 0.5 exhaust nozzle

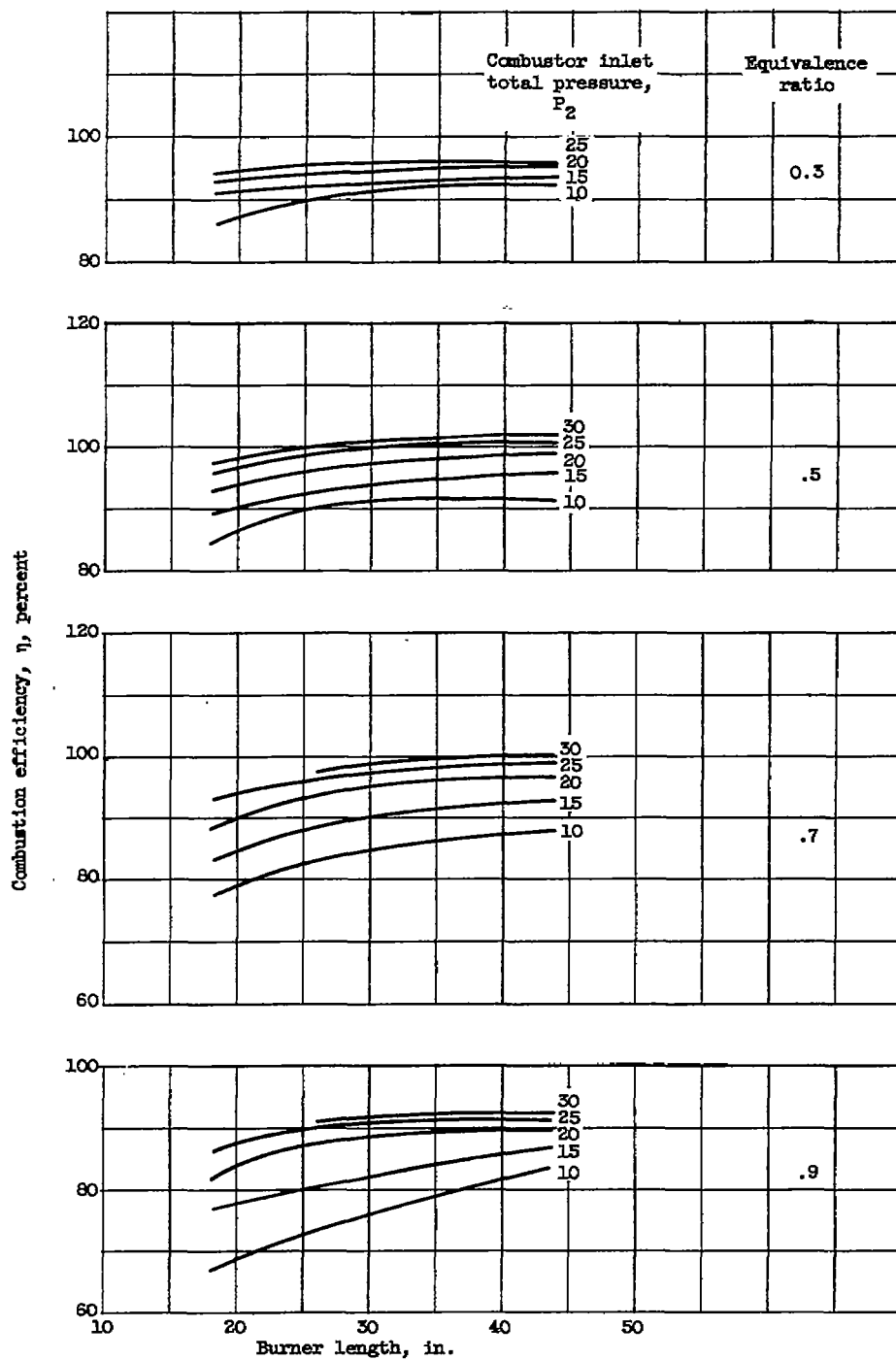Figure 13. - Continued. General performance characteristics of
configuration J.

(f) Burner length, 18 inches; 0.4 exhaust nozzle.

Figure 13. - Concluded. General performance characteristics of
    configuration J.

(a) Exhaust nozzle, 0.5.

Figure 14. - Effect of combustor pressure and length on combustion efficiency.

(b) Exhaust nozzle, 0.4.

Figure 14. - Concluded. Effect of combustor pressure and length on combustion efficiency.